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Influence of substrate moisture preparation on concrete overlay bond strength

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By

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Plagiarism Declaration

I declare that this dissertation is my own work. I have not plagiarised, nor tried to pass another authors work as my own. I have made every effort to ensure that where literature, discussions, collaboration, or contributions from other authors have been made, that it has been clearly acknowledged. This work has not been submitted previously at any other institution for any degree. This thesis is in submission of partial requirements for the degree of Master of Science in Engineering at the University of Cape Town.

Signature: …………………………   Date: …………………………

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Abstract

A considerable amount of progress has been made over the years in understanding the fundamentals of concrete composition and performance in both safe and harsh environments. Nevertheless, premature concrete deterioration remains a concern and is often experienced either due to poor workmanship or design. The bonded concrete overlay technique has become a popular method in repairing these deteriorated concrete structures, as it has a simplistic application procedure and can be applied to a number of different scenarios. This technique involves the removal of the distressed layer of concrete (substrate), followed by the application of a fresh, new layer of concrete (overlay). One of the fundamentals behind bonded concrete overlays is the bond between the existing and new concrete layer.

Sufficient bond strength is a prerequisite for the durability and serviceability of a repaired concrete structure. Factors which have been considered most important for achieving a good bond between the substrate and overlay are cleanliness and preparation of the substrate, together with overlay compaction and composition. However, the impact of substrate moisture condition on the bond strength of a repaired member has not been fully investigated and still raises many debates amongst engineers. Current best practice suggests that a concrete substrate which is preconditioned to a saturated surface dry state prior to overlay application will achieve higher bond strengths. This investigation provides insight into the aforementioned through both literature research and practical experiments performed.

In this investigation the effects of moisture preparation on bond strength were tested on three different substrate concretes, together with the application of four overlays. The substrates varied according to strength grade (50, 30 and 25 MPa), whereas the overlays varied in both strength (40 and 25 MPa) and workability (30 and 120 mm slump). The accompanied bond strength was established through interface shear testing. All substrates of the repaired specimens were subjected to a constant surface roughness and equally aged to prevent any differential shrinkage which may falsify bond strength readings. The bond strength results were plotted, statistically evaluated and compared with existing literature.

The results indicated that a saturated surface dry substrate concrete has no beneficial influence on the bond strength of the repaired specimen, and in many instances caused a negative response in comparison to non-preconditioned substrates. This phenomenon was attributed to better mechanical interlock, and is achieved when the fresh overlay can flow and interact with the unsaturated cavities and pores of the substrate. Furthermore, the results indicated that composition of the overlay through workability and strength, do influence bond strength.

Table of Contents

List of symbols and acronyms

The following symbols were used in this investigation:

DF:	degrees of freedom
M:	Moisture preparation
O1a:	Overlay mix (40MPa, 30mm)
O1b:	Overlay mix (40MPa, 120mm)
O2a:	Overlay mix (25MPa, 30mm)
O2b:	Overlay mix (25MPa, 120mm)
t:	test statistic
S:	Substrate
U:	Mean value
w/c:	Water/cement ratio
α:	Confidence level

The following acronyms were used in this investigation:

ANOVA:	Analysis of Variance
CSF:	Condensed Silica Fume
DI:	Durability Index
FA:	Fly Ash
GGBS:	Ground Granulated Blastfurnace Slag
ITZ:	Interfacial Transition Zone
OPC:	Ordinary Portland Cement
OPI:	Oxygen Permeability Index
SSD:	Saturated Surface Dry\

List of Figures

List of Tables

1. Introduction

1.1 Background and problem statement

Concrete structures have been around for many years and as a result, the number of concrete structures required to be repaired or retrofitted is growing in every major economy in the world. Presently, most concrete structures are either approaching, or have met the end of their design life (Beushausen & Alexander, 2005). This problem has compelled engineers to develop effective repair measures as appose to reconstruction which may not be economically viable. The selection of the appropriate repair measure often requires the consideration of compatibility concerns between new and existing concrete, as well as the cost versus the efficiency of the implemented repair procedure after application (Vaysbud & Emmons, 2006), (Schrader, 1992).

Bonded concrete overlays are particularly suitable for the application of large surface structures such as slabs on grade, pavements, bridge decks, walls and tunnels (Granju & Turatsinze, 2006). This repair process involves the application of a new concrete layer (overlay) to an existing concrete member (substrate). Overlays are applied over substrates to increase service-life, increase surface protection and create a more aesthetically pleasing concrete. Prior to the application of the overlay, the substrate surface is removed of any distressed concrete and prepared to ensure that a strong bond is formed between the two different concretes. (Indrajit *et al*, 2005). The region which represents the interaction between the substrate and overlay is known as the interface and is shown in figure 1.1.

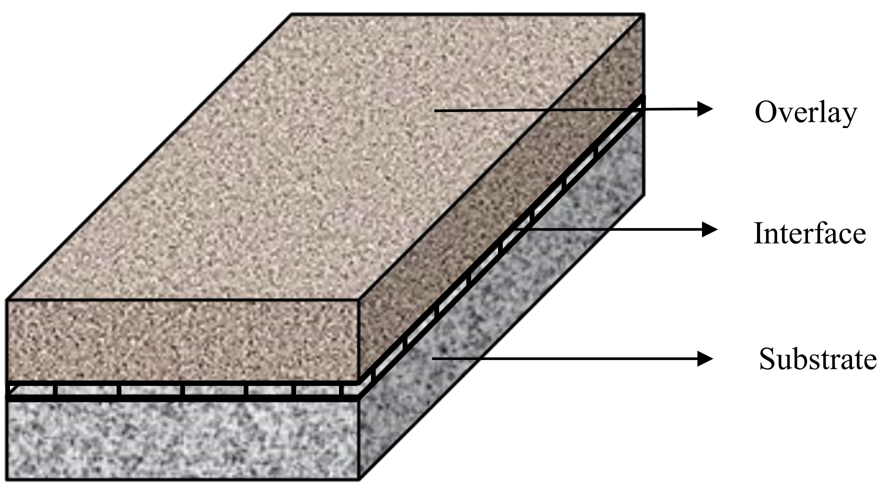


Figure 1.1: Bonded concrete overlay regions

The bond formed at the interface represents the constraining condition to whether the concrete was repaired successfully or not, and can be influenced by a number of different variables. One of which is the influence of moisture condition of the substrate prior to overlay application. It has been said that to provide for a stronger bond, the substrate should be in a saturated surface dry (SSD) state upon adhering the overlay. Over the years, this has become custom practice amongst contracting engineers. However, researchers Zhu, (1992), Silfwerbrand (2003) and Beushausen (2010) disagreed with the above mentioned statement and provided experimental data to prove their concerns. An added risk of subjecting the substrate to a SSD state is the possibility of having free standing water on the interface. This has the ability to diminish bond strength substantially, as pore water pressures are developed at the interface (Silfwerbrand & Beushausen, 2005).

1.2 Motivation of research

If the variables which affect the bond between concrete of different ages is not addressed, premature failure of repaired specimens may be experienced. This will in turn create added economic pressure, as well as doubt in future clients whether concrete repair and rehabilitation is worthwhile. Although a great deal of research has been performed with respect to how surface roughening, substrate cleanliness and overlay composition effect the bond strength, there are still many questions and very few answers as to what is the best moisture condition the substrate should be exposed to prior to overlay application, and if this relates to the type of overlay utilised.

Current practice suggests that the substrate should be in a SSD state prior to repair in order to achieve the best bond. However, many researchers Zhu, (1992), Silfwerbrand (2003) and Beushausen (2010) disagree with the above and believe that a dry substrate would probably provide better mechanical interlock between the substrate and overlay. Therefore further data is required to finally settle the ongoing debate, or provide valuable information in this regard, with particular interest in how different substrate moisture conditions interact with different concrete overlays.

1.3 Aim of research

This investigation aims to test how substrate preparation, together with overlay composition, influences bond strength. The parameters are assessed though statistical analysis and ranked accordingly to how they affect bond. The main aim of this investigation is to establish how substrate moisture preparation influences bond strength, and whether the way in which the substrate is prepared determines which overlay should be utilised.

1.4 Hypothesis

This investigation was performed under the hypothesis that pre-wetting the substrate to a SSD state would achieve no added strength gain in bond and in many cases reduce bond capacity. Secondly it was proposed that there would be a positive correlation between an increase in workability of the overlay mix and bond strength.

1.5 Objectives

The main objective of this thesis is to investigate the influence of substrate moisture preparation on overlay bond strength. In order to achieve the desired goal, the following secondary objectives must be met.

- Create a suitable knowledge base and identify the fundamental mechanics behind bonded concrete overlays and how they influence bond strength.
- Identify the appropriate mechanical test to be utilised to quantify a true reflection of bond strength.
- Investigate how substrate moisture preparation prior to overlay application affects bond strength through experimental testing.
- Analyse the results of the experiments performed and relate to the existing literature to justify findings or to create a new understanding of the concrete repair process.

The above stated objectives represent the primary core behind this particular investigation, and although not ultimately the aim, these objectives will provide valuable information in creating a guideline for bonded concrete overlay repairs.

1.6 Scope and limitations

Due to the nature of this investigation, not all of the factors which influence bond strength of concrete overlays and hence durability was considered. Therefore, the following represents the scope and limitation of this investigation:

- The concrete substrates were restricted to three different grades, all comprising of conventional Portland cement. These included a strong impervious concrete, a moderate strength concrete and a low strength, poor grade concrete.
- The applied overlays comprised again of conventional Portland cement and did not include any admixtures or fibres. The composition of the overlays varied in order to create 4 different overlay mixes, with each mix varying strength and workability.

- The moisture conditions of the concrete substrates prior to overlay application were limited to four states. Two of which involved substrate pre-wetting.

- Testing of the bond strength was limited to the interface shear test method and hence did not include any tensile testing.

- Curing, substrate roughening and overlay compaction was maintained constant throughout the investigation.

- Shrinkage of the overlay concrete was not considered in this investigation.

The aforementioned points represented the boundary of this investigation and created a platform in which the impact of substrate moisture preparation could be quantified, together with the influence of mechanical overlay properties.

1.7 Outline of thesis

This investigation comprises of five separate chapters, namely: Chapter one, which provides a brief background and introduction to the scope and motivation behind the investigation; in Chapter two, the relevant literature which encompasses the bonded concrete overlay and factors effecting bond of repaired members are discussed and reviewed; Chapter three discusses the materials and method behind the experimental procedure; Chapter four discusses the results and any trends which emerge thereof; lastly chapter five provides conclusions and recommendations with respect to the investigation.

2. Literature Review

2.1 Introduction

This chapter contains a comprehensive study behind experimental work performed by various researchers regarding the background properties which govern the behaviour of materials in terms of concrete repair, as well as measures utilised by civil engineers in order to ensure the successful response of the repaired concrete when exposed to the environment.

Although many different concrete repair methods will be mentioned in the literature review, the main focus will be based on the bonded overlay technique and the factors involved. Case studies and previous experiments performed on the mentioned concrete repair method are also included.

2.2 Concrete properties

2.2.1 Introduction

Of all breakthroughs in human progress over the years, concrete can be considered one of the more significant with regard to construction. Concrete has become the most widely used man made building material and without it, the world we see today would be unobtainable. Although concrete may seem like a simple building material at first glance, there are many factors which can be manipulated within the mix in order to achieve a concrete which is best suited for the construction application it finds itself in. It is also important to note that in order to truly understand the factors which cause concrete damage and as a result lead to concrete repair techniques, a great understanding of the chemical and physical processes which govern concrete is required.

This chapter will provide valuable insight into the constituents which make up concrete as well as provide information regarding concrete properties which can be expected in both the fresh and hardened state.

2.2.2 Cementitious materials

Cement is regarded as one of the more important inputs into the composition of concrete and is generally defined as the binder or adhesive which provides for the strong rigid composite. Although there are many different types of cement available, cementitious materials used for construction purposes generally consist of Portland cement (Grieve, 2009).

The name "portland" cement originated from a man named Joseph Aspdin in 1824 to describe the new cement which he later patented in England. This particular cement is chemically formed by combining raw materials containing calcium oxide (CaO), silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3). In order to achieve the final grey powder (portland cement), the mixture of raw materials are heated to extreme temperatures inside a kiln to form clinker and then crushed with a small amount of calcium sulphate (Nmai *et al,* 2001) Figure 2.1 illustrates the manufacturing process of portland cement.

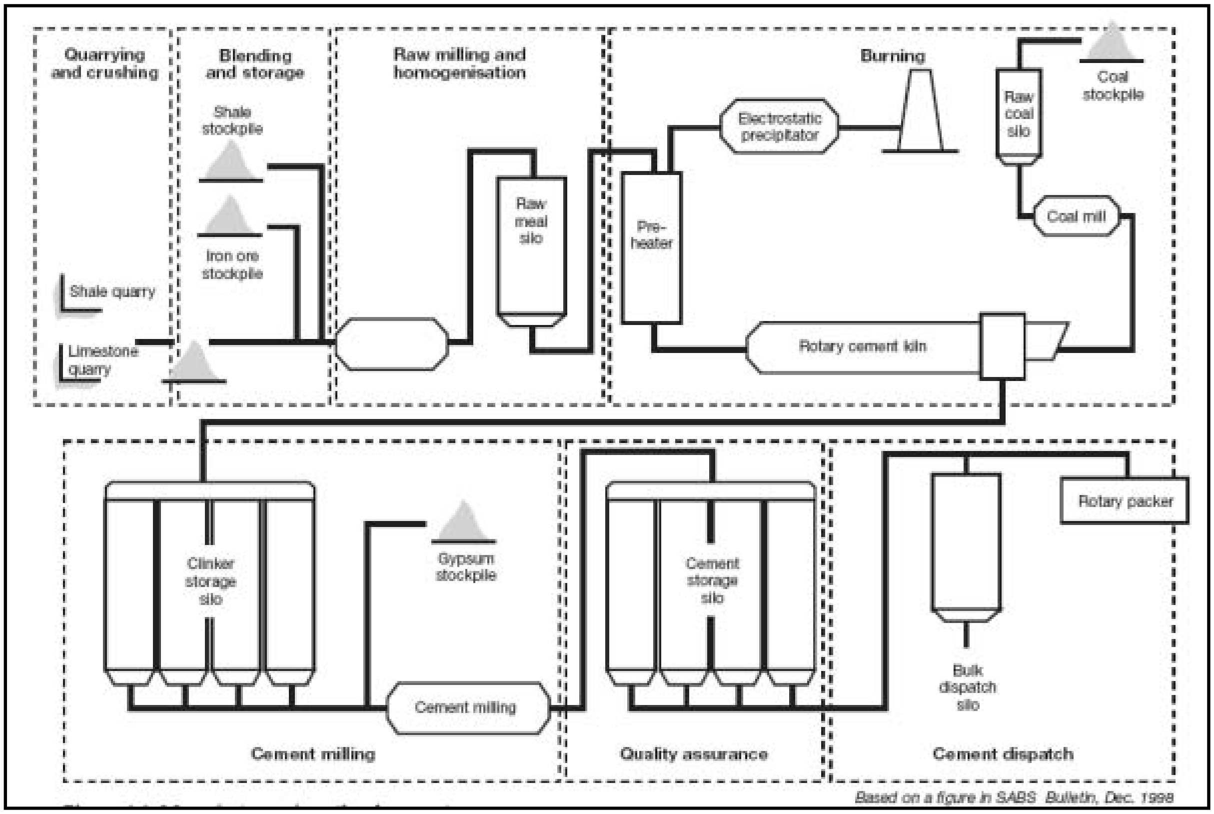


Figure 2.1: Manufacture process of portland cement (Nmai *et al,* 2001)

Although each manufacturer of portland cement uses a different brand name, the processes involved are generally very similar to what is illustrated in figure 1. As mentioned before portland cement is chemically composed of various different raw materials. High quality cement requires the use of raw materials of proper composition and proportioned to precise quantities. Table 2.1 provides a summary of where these raw materials are obtained from (Nmai *et al,* 2001).

Table 2.1: Origin of cement raw materials

Origin of raw materials for cement production				
Lime (CaO)	Iron (Fe_2O_3)	Silica (SiO_2)	Alumina (Al_2O_3)	Clacium Sulphate
Alkali waste	Blast furnace dust	Calcium Silicate	Aluminum ore refuse	Anhydrite ($CaSO_4$)
Calcite	Clay	Cement rock	Bauxite	Hermihydrate ($CaSO_4.1/2H_2O$
Cement rock	Iron ore	Clay	Cement rock	Gypsum ($CaSO_4.2H_2O$)
Chalk	Mill scale	Fly ash	Clay	
Clay	Ore Washings	Fuller's earth	Copper slag	
Dolomite	Pyrite cinders	Limestone	Fly ash	
Limetstone	Shale	Loess	Fuller's earth	
Marble	Fly ash	Marl	Granodiorite	
Marble		Ore washings	Limestone	
Seashells		Quartzite	Loess	
Shale		Rice hull ash	Ore washings	
Slag		Sand	Shale	
		Sandstone	Slag	
		Shale	Staurolite	
		Slag		
		Traprock		

There are four different compounds, together with calcium sulphate which are formed in the clinker whilst the raw materials are placed in the rotary kiln. These compounds may be available in different quantities as well as ground to different finesses in order to achieve various forms of portland cement. The compounds are presented in table 2.2 together with full and shorthand notation.

Table 2.2: Chemical compounds present in cement

Compound name	Chemical formula	Shorthand notation
Tricalcium silicate (alite)	$3CaO \cdot SiO_2$	C_3S
Dicalcium silicate (belite)	$2CaO \cdot SiO_2$	C_2S
Tricalcium aluminate	$3CaO \cdot Al_2O_3$	C_3A
Tetracalcium aluminoferrite (ferrite phase)	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF

The main chemical reaction which hydraulic cement undergo is a process known as hydration. Hydration causes portland cement and hence the concrete in which the cement forms part of to harden and gain strength. In the hydration process there are four main reactions which take place, each producing a product which leads to the hardening of concrete. Figure 2.2 Shows how each of the four compounds develop strength over a period of time. C_3S gains most of its strength in the first two to three days, where as the C_2S compound is responsible for the long term strength. C_3A and C_4AF primarily contribute to early strength gain of the concrete (Nmai *et al,* 2001).

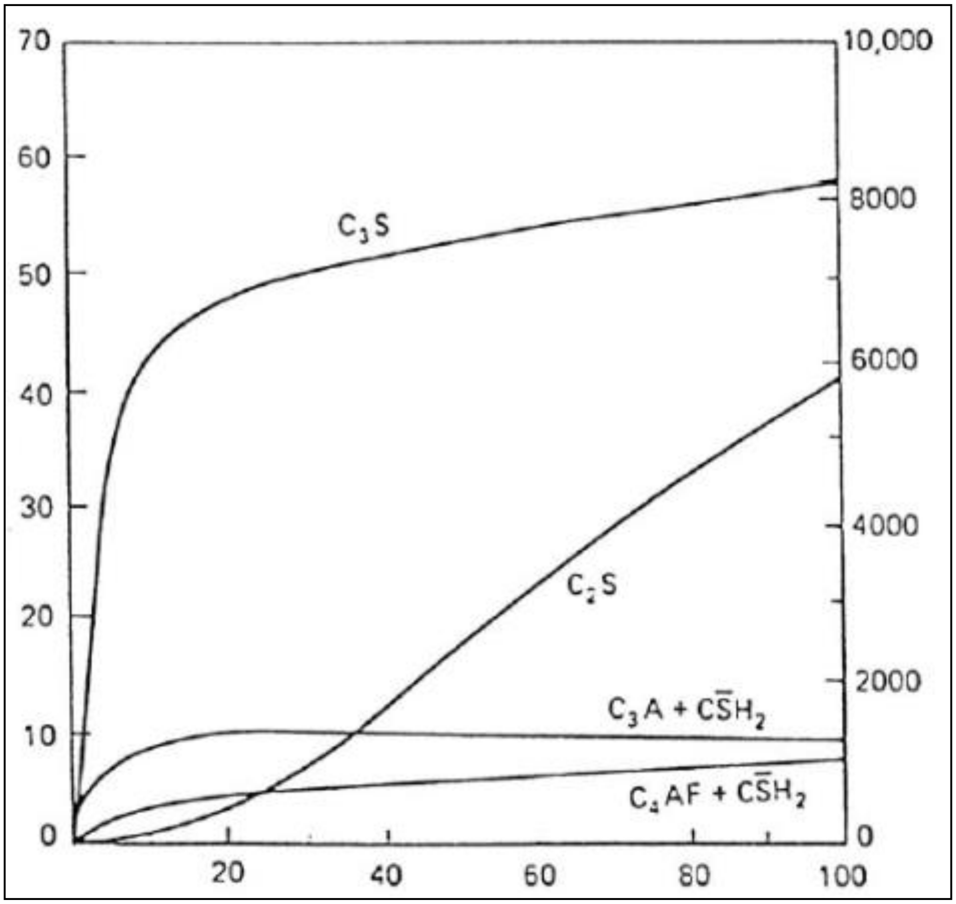


Figure 2.2: Strength development of cement (Nmai *et al,* 2001)

2.2.3 Chemical admixtures

Chemical admixtures are specific materials which are utilised in order to enhance the properties of both fresh and hardened concrete, whether it is by physical or chemical processes. According to Marais (2009), the properties of fresh and hardened concrete can be modified in the following ways:

Fresh concrete

- Increase the slump of the concrete mix without increase the water content
- Reduce the water content without changing the slump of the concrete mix
- Adjust the setting time of concrete
- Reduce segregation and bleeding
- Improve the pumpability of a concrete mix

Hardened Concrete

- Accelerate or retard the rate of strength development in the early ages of the concrete
- Increase the strength of the concrete without increasing the cement content
- Improve potential durability and reduce permeability

Admixtures are generally supplied as aqueous solutions, but can also be used in powder form. In many instances admixtures are a blend of several chemicals in order to influence a wide variety of properties within the concrete mix. There should be no confusion with the use of admixtures and that of any other materials which are inter-ground or pre-blended with the cement. Any fibres, pigments, lime stone powders or supplementary cementitious materials such as FA, CSF or GGBS are not chemical admixtures (Marais, 2009). While utilising chemical admixtures, particular attention must be given to the quantity implemented into the concrete mix. A common malpractice is the overdosing of chemical admixtures, with the perception that more is better. Overdosing may result in retardation, settlement, bleeding, segregation and excess air entrainment of the concrete mix. All of the above result in a concrete with reduced strength and durability properties.

Chemical admixtures, if properly utilised, can produce beneficial results and save both time and money when designing a concrete mix. However one must not forget the negative aspects which arise from overdosing. Therefore trial mixes should always be practiced when using chemical admixtures, in order to attain the most efficient and effective blend of concrete constituents.

2.3 Types of concrete damage

In order to attain a better understanding about the concept of concrete repair, one needs to understand the mechanics behind the different forms of concrete damage. Below the different types of concrete damage are described in terms of mechanical/physical damage and chemical damage.

2.3.1 Mechanical and physical processes

Abrasion

Abrasion refers to the wearing or repeated rubbing of the concrete element which is exposed to the environment. The resistance to abrasion of the concrete is primarily determined by the hardness and quality of the aggregate and not the cement paste (Ballim *et al*, 2009); however this does not imply that the water to cement ratio (w:c) of the concrete is of no importance to abrasion resistance. Previous studies have shown that the abrasion resistance of the concrete increases linearly with a decrease in w:c (Boddy *et al* 1999), (Smith, 1956).

Erosion

Erosion of the concrete surface refers to the abrasive action of fluids and suspended particles such as wind-borne sand particles. Therefore erosion can be regarded as a special case of abrasion (Ballim *et al*, 2009). Erosion leads to the directed and focussed stress application on the concrete surface and has the ability of causing aggregate particles to be dislodged from the surface. Therefore it is recommended that smaller sized aggregate be used for concrete exposed to extreme cases of erosion (not greater than 20mm), especially in the instance where cavitation erosion is present. This type of erosion is prevalent in dams, spillways, channels and other hydraulic structures (mowber, 2000).

Freezing and Thawing

Problems encountered in concrete due to this phenomenon is not common in Southern Africa due to the generally mild winters compared to that of the northern hemisphere; however there are instances where the concrete needs to be designed for the use in cold rooms or cold liquid storage facilities. Damage from freezing derives from the fact that water undergoes a volume increase of about 9% when turning into ice (Ballim *et al*, 2009). Thus damage of the concrete occurs when the water present in the pore structure freezes, with no excess space to accommodate for the expansion. Tensile stresses are then created within the concrete member which lead to micro cracking of the cement paste.

2.3.2 Chemical processes affecting concrete

There are many chemical environments which are considered to be harmful to concrete members. These include external factors which deteriorate the concrete material, as well as the reinforcing steel of the concrete member. Concrete is also susceptible to chemical attack within the concrete structure, due to the presence of alkalis. The different forms of chemical attack which lead to concrete deterioration are provided within this section.

Acid attack

This form of chemical corrosion is attributed to the exchange reactions between acids (both organic and inorganic) and components of the hardened cement paste. Concrete is regarded as being generally basic or alkaline in nature and as a result the products of hydration as well as any unhydrated cement react with acids. This ultimately leads to the destruction of the cement paste matrix through the removal of Ca^{++} ions as soluble products (Ballim *et* *al*, 2009). Equation 3 represents the reaction of the acid (HCL) and the calcium hydroxide ($Ca(OH)_2$) of the unhydrated cement within the concrete.

$$\boldsymbol{Ca(OH)_2 + 2HCL \rightarrow CaCl_2 + 2H_2O} \qquad \textbf{Equation 1}$$

The water soluble calcium compounds are produced which are then leached away, exposing the aggregates and resulting in debonding of the concrete itself. The rate of the dissolution which occurs due to the acid attack is governed by the pH level of the acid. The lower the pH level the higher the dissolution rate. As mentioned previously there are two types of acid attack, namely: organic and inorganic acids. The organic acids are less severe in concrete deterioration than the inorganic acids which originate from industrial chemicals. In order to minimise the effects of acid attack, concrete can be designed for low permeability in order to restrict the movement of the acid and limit the reaction process.

Sulphate attack

Concrete can also deteriorate in the presence of sulphuric acid produced from either sewage or sulphur dioxide which is present in the atmosphere of industrial cities (Attiogbe & Rizkalla, 1988). The susceptibility of concrete to undergo this form of chemical attack is primarily attributed to the high alkalinity of Portland cement; however the reason why sulphuric acid is particularly harsh is due to the sulphate ion participating in the sulphate attack in addition to the dissolution caused by the hydrogen ion.

The reaction process involves the sulphate ions permeating through the concrete and chemically producing gypsum and ettringite. This results in the concrete expanding and causes internal stresses which lead to cracking and debonding of the concrete member (Ballim *et al*, 2009).

Alkali-silica reaction (ASR)

The term ASR represents the reaction between alkalis and certain mineral constituents in some aggregates which cause expansion within the concrete and consequent cracking. This ultimately renders concrete unsightly and deteriorates its engineering properties. One of the main concerns with regards to this particular chemical attack is that the concrete reinforcement is less well protected from the elements and thus incurs reinforcement corrosion (Oberholster, 2009).

ASR is different from the other forms of chemical attack, in that the chemical reaction conducts itself within the concrete member and is not a result of the absorption properties of the concrete. The reaction takes place between the alkaline pore structure of concrete and metastable forms of silica. This produces the expansive alkali-silica gel which in turn creates internal stresses within the concrete and ultimately leads to cracks.

Although ASR is very destructive, there are three prerequisites which need to be met simultaneously before the reaction can take place (Oberholster, 2009).

- A pore solution which is sufficiently high in alkalinity is required.
- There must be a sufficient amount of deleteriously reactive minerals present in the concrete aggregate
- The environmental conditions must be suitable to promote the reaction (i.e. sufficient moisture)

With these three factors present in a concrete member, ASR will commence and will continue to cause problems unless either one of the three factors are removed from the situation i.e. The reactive minerals in the aggregate have completely diminished, no longer supporting a reaction or the concrete member is separated from environmental influences.

Reinforcement Corrosion

Over the past two to three decades, reinforcement corrosion has been reported in the literature in great detail and is regarded as one of the more concerning topics which lead to concrete deterioration (Ahmad, 2003). Reinforcement corrosion is induced by two main factors, namely: carbonation of the concrete cover, and the penetration of chlorides either contained in the marine environment or in chemicals which are in contact with the concrete. The composition of the concrete itself can also play a part in initiating reinforcement corrosion; however this is less common (Martínez & Andrade, 2009).

With the above mentioned it is not accurate to say that all concrete members will undergo reinforcement corrosion which will result in the structure's ultimate failure. Concrete normally provides a high degree of resistance against the corrosion of reinforcing steel, by virtue of its high alkaline content (pore solution pH > 13.5). Under this pH level the steel remains passivated and does not undergo any anodic or cathodic half reactions, common to steel corrosion (Ahmad, 2003). Furthermore, a concrete which has a well-consolidated composition together with a low w/c ratio and proper curing techniques instilled, will result in the aggressive corrosion inducing agents being restricted from penetrating the concrete due to its low permeability. These factors all result in a durable concrete, which unfortunately are not always met in practice.

Concrete susceptible to steel corrosion will result in cracking (which will further increase corrosion and decrease durability), reduction of bond strength, reduction of steel cross section and loss of serviceability. In extreme cases, reinforced concrete undergoing steel corrosion does not only portray poor structural performance but can also result in the loss of structural integrity (Cabrera, 1996).

The reactions at the anodes and cathodes of a reinforced concrete member are illustrated in figure 2.3 and are broadly known as 'half-cell reactions'. The oxidation process, which is the anodic reaction, results in the loss of metal and hence the reductions of steel cross section. The reduction process represents the cathodic reaction and is responsible for the reduction of dissolved oxygen which forms hydroxyl ions. Equations 2-5 represent the common anodic reactions, where equation 6 represents the cathodic reaction (Ahmad, 2003).

$$3Fe + 4H_2O \rightarrow Fe_3O_4 + 8H^+ + 8e^-$$ **Equation 2**

$$2Fe + 3H_2O \rightarrow Fe_3O_4 + 6H^+ + 6e^-$$ **Equation 3**

$$FE + 2H_2O \rightarrow HFeO_2^- + 3H^+ + 2e^-$$ **Equation 4**

$$Fe \rightarrow Fe^{2+} + 2e^-$$ **Equation 5**

$$2H_2O + O_2 + 4e^- \rightarrow 4OH^-$$ **Equation 6**

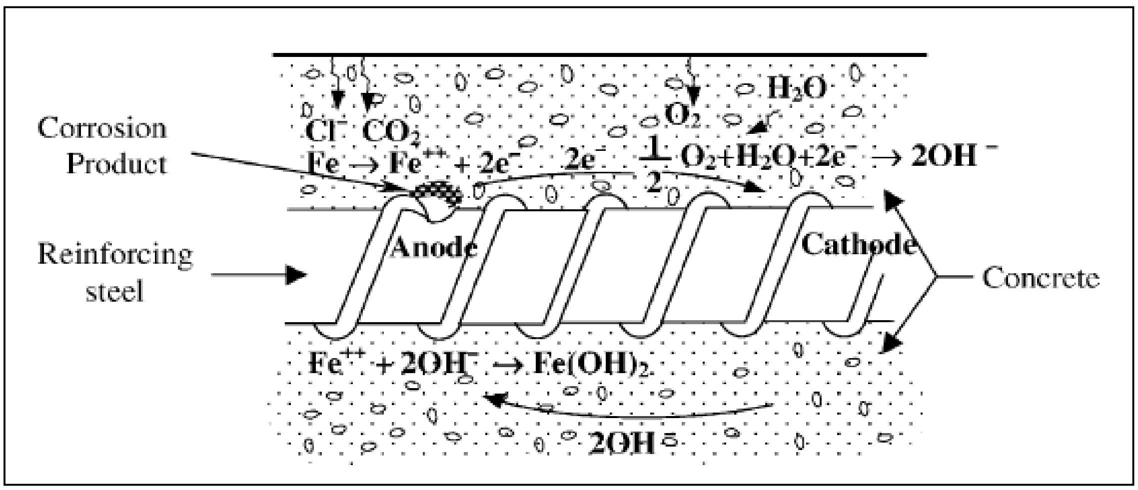


Figure 2.3: Corrosion of reinforcement steel in concrete (Ahmad, 2003)

The above mentioned forms of concrete deterioration by chemical reaction are summarised in figure 2.4 and represent the basic destructive chemical reactions which concrete experiences. From the above it is clear just how important it is to design not only for strength but also for durability concerns.

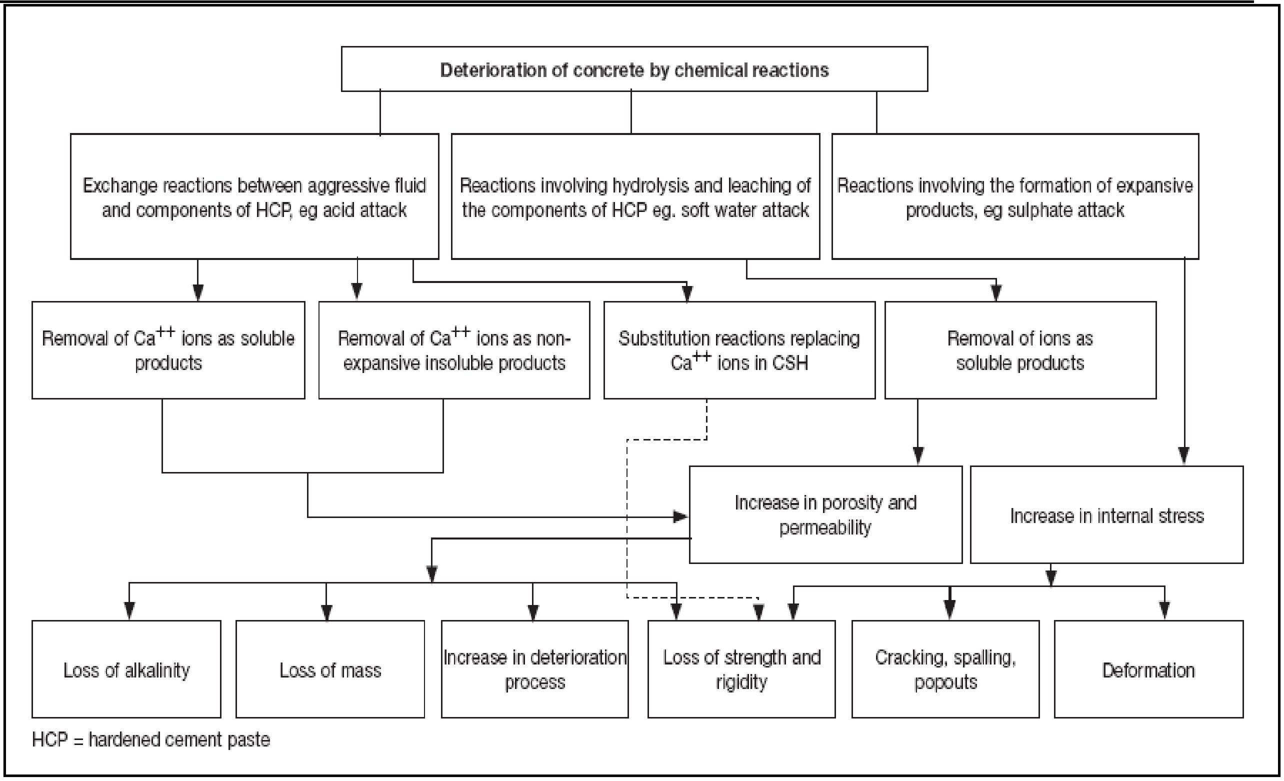


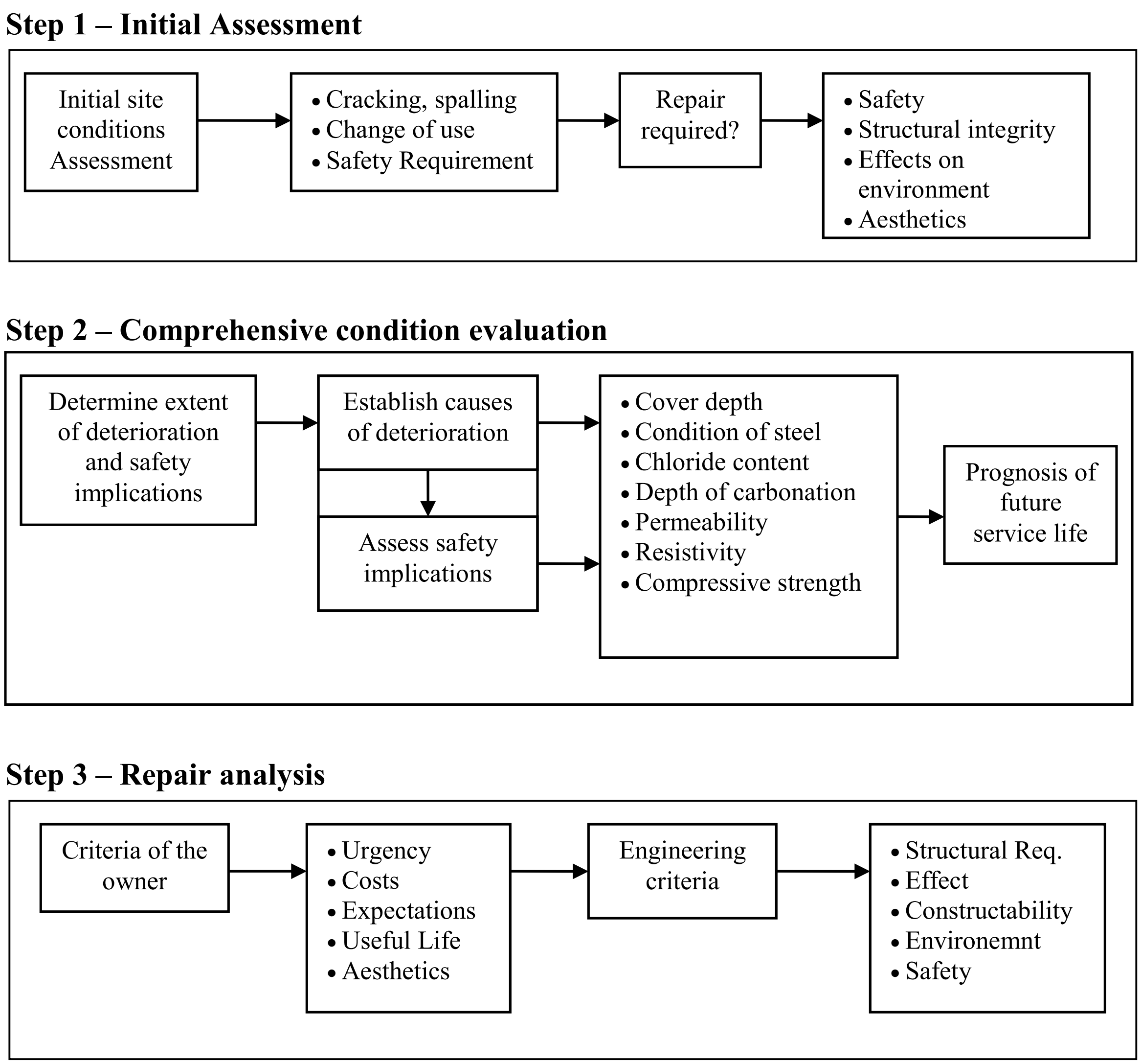
Figure 2.4: Deterioration of concrete by chemical process (Ballim *et al* , 2009)

2.4 Concrete evaluation and repair process

In the past concrete repair was merely seen as an informal necessity for concrete structure owners; however as the years have passed on, so has this perception of concrete repair. The concrete repair industry has grown into a worldwide multibillion entity, which provides the necessary support for modern concrete infrastructure (Emmons, 2012). The problem is that although the concrete repair industry has grown rapidly, there still remains an unacceptably high failure rate of repair measures implemented. This is either attributed to the lack of professionalism/workmanship by the contractor or lack of knowledge of the causes of concrete damage and necessary practices required to repair and prevent the concrete deterioration process from resurfacing. For this very reason tireless effort has been put in terms of concrete repair evaluation systems, which guide engineers in making the correct decisions regarding concrete repair.

2.4.1 Condition evaluation process

The concrete repair process can be regarded as a man-made complex system, involving many factors which cannot be considered in isolation, but rather are interconnected and interdependent (Vaysburd & Emmons, 2006). Therefore in order to properly repair the material, an investigation needs to be performed in identifying the problem which caused the concrete failure and how one needs to address it. There are many different methods which can be used in evaluating the damaged concrete and at the same time establishing a plan of action which is holistic in nature. Figure 2.5 portrays a concrete repair process which provides the necessary framework to ensure the successful completion of the repaired concrete.



Step 4 – Remediation alternatives, repair options and execution

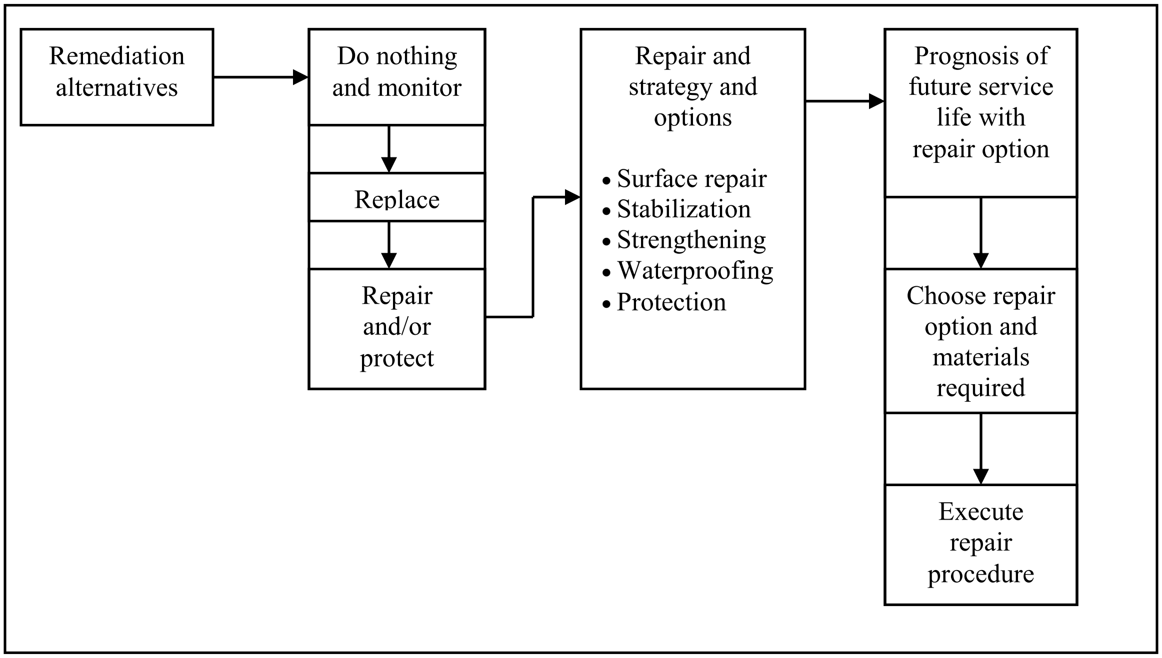


Figure 2.5: Four step repair process (Vaysburd *et al,* 2009 & Vaysburd *et al*, 2006)

The above concrete repair process was adapted from (Vaysburd *et al*, 2009) and (Vaysburd & Emmons, 2006). Each step provided represents an important procedure which needs to be performed in order to ensure that the concrete repair process is not just a remedial activity, but rather a science. This will allow for greater success in repair projects and limit the amount of material wastage. Figure 2.5 portrays concrete repair in a four step process, namely: Initial Assessment, Comprehensive condition evaluation, repair analysis and remediation alternatives, repair options and execution.

Initial assessment

The initial assessment of a concrete structure is one where the main priority is to see whether repair is required or not. The inspection is performed on the basis of a site visit with no complicated concrete testing involved. The initial assessment may commence due to visible concrete damage or to investigate whether the existing concrete structure is suitable for a change in structural use. One of the more serious factors which are considered in the initial assessment is the safety of the existing building and whether concrete repair will positively enhance the situation. If concrete repair is required, the engineers will move on to the second step of the repair procedure.

Comprehensive condition evaluation

This is included to determine the extent of the concrete deterioration, as well as to establish the causes of the problem. The investigation will include checking for chloride content in the concrete, condition of reinforcing steel, cover depths, concrete resistivity and relating this to the concrete application and environment. From the data acquired, the future life of the structure is determined taking into account safety implications.

Repair analysis

The repair analysis takes into account the views of both the engineer and the owner. From this information a plan of action is developed which has the clients and engineers best interests at heart with regards to costs and structural integrity. This will then lead onto different repair options available and the execution of them.

Remediation alternatives, repair options and execution

The final step in the repair procedure is to provide for remediation alternatives as well as providing the different options available in terms of concrete repair. Each repair strategy will include a detailed report on how it will be implemented, together with a set of pros and cons and an estimation of how the service life of the structure will be enhanced. Once the preferred repair option is selected, all that remains is the execution of the well-developed plan.

A repaired concrete structure is one which comprises composite materials interacting in a complex environment. Therefore if one had to analyse the process structurally, three basic phases would be found i.e. the existing substrate, the repair material and the transition zone between them (Vysburd & Emmons, 2006).

Repair measurement techniques

The repair procedure mentioned above can only be implemented if the appropriate concrete evaluation measures are carried out depending on the extent of concrete damage experienced. The table below was adapted from (Bissonnette *et al*, 2013) and represents the different destructive and non-destructive concrete tests available according to EN 1504-10 and ACI 364.1-R07.

Table 2.3: Concrete deterioration tests

Characteristic	Test procedure	Requirements
Delamination	Hammer sounding	No delamination
Surface tensile strength of substrate	Pull of test	≥ Adhesion (1.5–2 MPa)
Crack movement	Mechanical/electrical gauge	No crack movement
Crack width and depth	Mechanical/electrical gauge,	
	Core and visual/ultrasonic	
carbonation depth	Phenolphthalein test,	< Cover depth
	Concrete cover	
chloride content	Site sampling and chemical analysis	See guidelines
Rebar corrosion	Half cell potential mapping	See guidelines
Penetration	Site sampling and chemical analysis	See guidelines
Compressive strength	Core and crushing test	Depends on structural behaviour and design
	Rebound hammer	

2.5 Different concrete repair applications

The number of different concrete repair techniques has increased substantially since the 1960's (Morgan, 1996), with each having the ability to be customised to provide for the best repair solution of deteriorated concrete. As mentioned previously, the bonded concrete overlay repair method is one of the more popular methods as its simplicity and diverse application procedure is something that engineers appreciate. Further discussion of the bonded concrete overlay is provided in section 2.6

The selection of the appropriate repair option is something which is determined from the aforementioned repair evaluation process (section 2.4). Here, the selected repair measure must be suitable for the degree of concrete deterioration, but at the same time economical. Cusson & Mailvaganam (1996) explained how concrete patching repair materials can be utilised to achieve two different outcomes:

- Non-structural repairs (figure 2.6) – Here, the concrete rehabilitation process is one which restores the appearance of the structure, but at the same time reducing permeability, protecting steel reinforcing bars from corrosion and improving abrasion resistance.

- Structural repairs (figure 2.7) – The concrete repair process is utilised to restore structural loading capacity of the damaged concrete member; or, increase the load bearing capacity of a member which has been under designed.

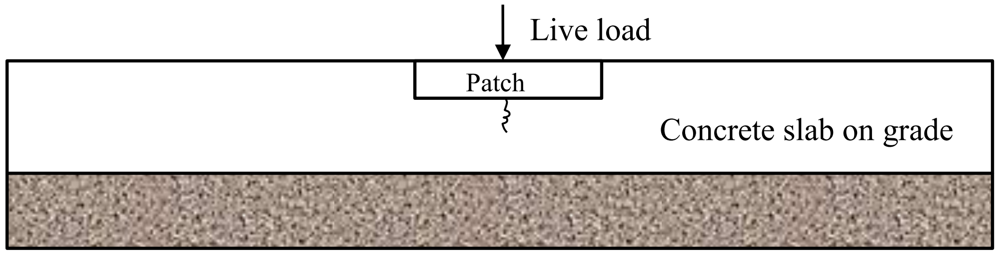


Figure 2.6: Non-structural load

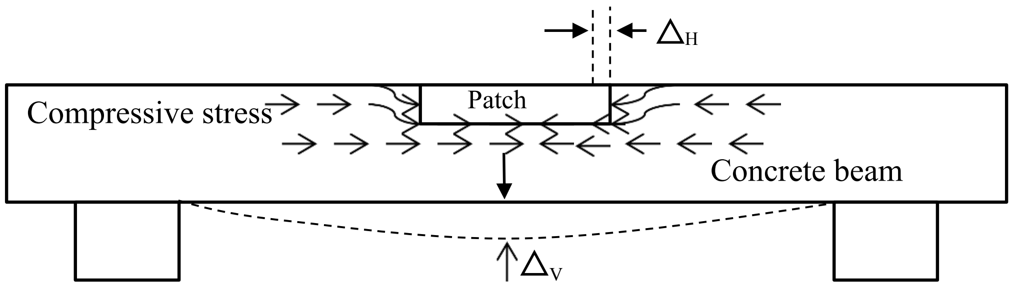


Figure 2.7: Structural load

To further quantify the different types of concrete repair, table 2.4 was created from Robery & Shaw (1997). The non-structural repairs were further broken down into various categories, namely: Ingress protection, Moisture control, Concrete restoration, Concrete bonding, Chemical resistance etc.

Table 2.4: Summary of concrete repair techniques

Specific property	Repair principle	Specific property	Repair principle
Ingress protection	Surface impregnation	Concrete bonding	Injecting for continuity
	Surface coating	Physical resistance	Overlays/Coatings
	Crack sealing		Impregnation
Moisture control	Surface treatment	Chemical resistance	Overlays/Coatings
	Surface coating		Impregnation
Concrete restoration	Bonding mortar	Restoring passivity	Replacing concrete
	Recasting with concrete		Realkalisation by diffusion
	Spraying concrete mortar	Increasing passivity	Limiting moisture content
Structural strengthening	Installing ties or anchors	Corrosion control	Limiting oxygen content
	Steel plate bonding	Control of anodic areas	Active reinforcement coatings
	Adding mortar or concrete		Barrier coatings on rebar
	Injection		Anodic inhibitors in concrete

From table 2.4 it is clear that there are a number of different repair techniques available depending on the nature of the deteriorated concrete. However, in many instances, the concrete repair can prematurely fail and as a result, once again expose the existing member to elements which led to its deterioration. The following figures, 2.8 a), b) and c) illustrate the common failure pattern when applying repair mortars on to an existing substrate surface for either non-structural or structural repairs.

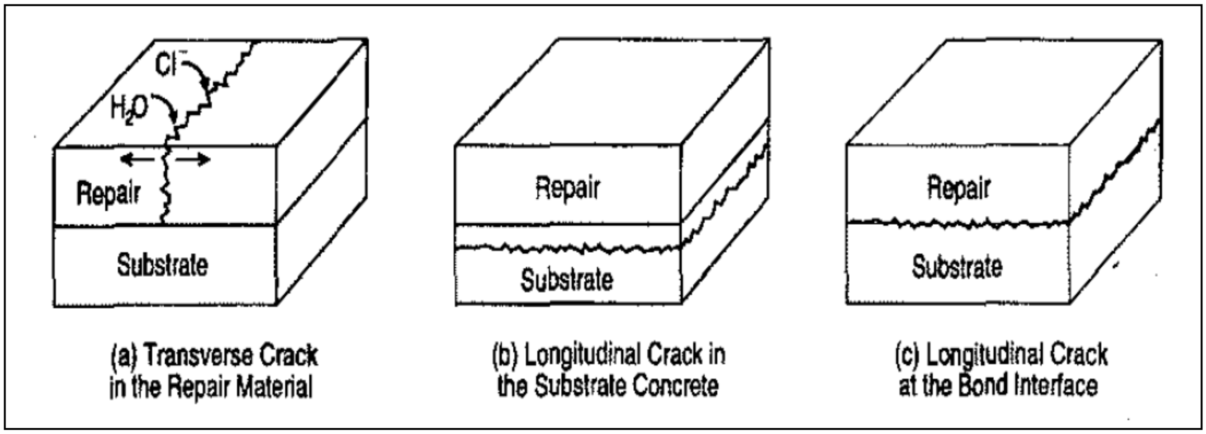


Figure 2.8: Failure mechanisms in patch repairs (Cusson & Mailvaganam, 1996)

Tensile cracking

This form of failure as illustrated in figure 2.8 a) represents the situation where the tensile strength of the applied overlay is weaker than both the developed bond and strength of the substrate. The cracking will promote ingress of salts and chlorides and ultimately lead to concrete delamination through freeze – thaw cycles.

Shearing of substrate concrete

The failure mechanism illustrated in figure 2.8 b) is characterised by the shearing of the substrate surface, and is experienced when the interface bond strength and tensile strength of the overlay are both stronger than the shear capacity of the substrate. Failure is manifested with the delamination of the overlay patch, with a percentage of substrate adhering.

Failure at the interface

The last failure mechanism represented in figure 2.8 c) is categorised by failure at the interface between the overlay and substrate. The bond strength in this case is weaker than both the substrate and overlay patch material and hence results in interface failure.

The above mentioned was a brief summary of the different repair measures as well as failure mechanisms which are experienced when concrete repair is not carried out in a professional manner. As mentioned before the bonded concrete overlay is probably the most popular and widely used technique. To provide further insight into the fundamentals and processes involved behind this repair process, section 2.6 was compiled.

2.6 Bonded concrete overlay repair

Bonded concrete overlays have become a widely accepted practice for repair, rehabilitation and strengthening of concrete members. Despite the ever increasing use of the repair method, failure of overlays is commonly witnessed in engineering practice due to overlay cracking and debonding (Alexander & Beushausen, 2009). There are many causes for the failure of overlays which include; substrate surface preparation, choice and application of overlay materials, curing procedures and environmental influences. However, in general, the main contributors to the failure of concrete repaired members are accepted to be a cause of poor workmanship and the differential shrinkage between overlay and substrate material.

Although the bonded overlay technique is extensively used to extend the life of concrete members, the scope and detail in which the method is presented in terms of construction codes is insufficient and often requires the professional judgment of the engineer in question. Therefore to try and understand the process of concrete repair, one should look at the problem in terms of two component systems being linked (i.e. the concrete overlay and substrate and the repaired material and repaired concrete). L Czarzecki (2009), explained that the main factor which affects the durability and the reliability of the repaired member is due to adhesion between the two different systems. Good adhesion is a component of surface science of the substrate and material properties of overlay and substrate. Figure 2.9 illustrates the two different systems mentioned above and how they should be prepared together with steel reinforcing to provide for a strong bond.

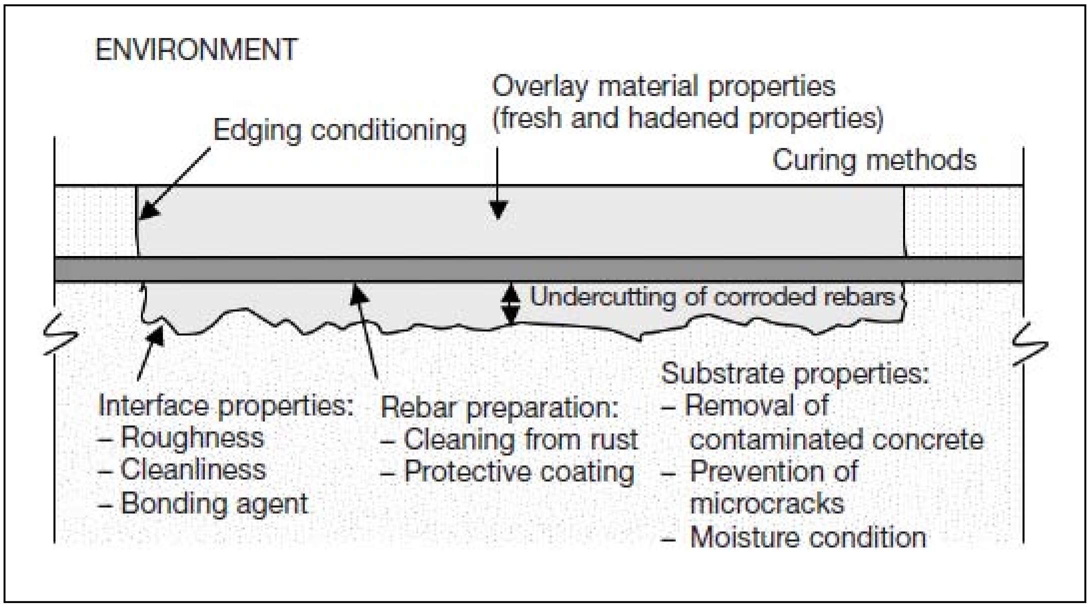


Figure 2.9: Factors influencing bonded overlay (Beushausen & Alexander, 2009)

2.6.1 Definition of bonded concrete overlays

An overlay is regarded as a layer of concrete or mortar whose main purpose is to restore or improve the function of the previous surface to which it was applied. The overlay is usually greater than 25mm thick and can also be polymeric in nature. (ACI, 2008)

2.6.2 Application of bonded overlays

Bonded concrete overlays are very versatile in its application. Not only can they be utilised for structural purposes, but they can also be used in a decorative manner. Common overlay application techniques include: patch repairs, shotcrete linings of tunnels, slabs on grade, in and outdoor repairing of retaining walls and repairing of bridge decks (Banthia *et al,* 1996). Concrete bonded overlays also have the ability to be applied on precast concrete elements as an in situ topping (Beushausen, 2006). Examples of the application procedure are illustrated in figures 2.10 – 2.13.

The figures reiterate the diverse environments which concrete overlays are exposed to, and why they are such a popular concrete repair procedure. Allen *et al* (1992) highlighted that if the bonded concrete overlays are applied properly with no short cuttings, then the following positive benefits can be achieved.

- Restoration of durability.
- Restoring structural integrity i.e. strength, abrasion resistance, etc.
- Increased structural strength of overlayed surface.

- Restoring or improving appearance of the pavement.
- Restoring the structure's fitness for use

Figure 2.11: Shotcrete applied to a vertical wall (www.dcnol.com)

Figure 2.10: Slabs on grade for parking (www.merchant circle.com)

Figure 2.13: Overlay repair on concrete footpath (www.gaddis&sonnic.com)

Figure 2.12: Overlay application on slabs on grade (www.cement.org)

The problem with the above however, are that many engineers do not understand the required procedures which need to be implemented before a positive outcome can be achieved. This leads on to the next section of this chapter. Here, the different factors which influence the bond strength and hence durability of the repaired member is discussed.

2.6.3 Fundamentals of bond mechanics

One of the fundamental concerns or primary aspects of preparing the substrate prior to overlay application is to maximise the adhesion between the two different systems. Adhesion between the repair material and substrate is an important aspect in concrete repair irrespective of whether the repair procedure implemented is for structural or non-structural purposes (Czarnecki, 2009). The adhesion of the repair joint can be considered effective if it promotes the load transfer and ensures even distribution of stresses.

Adhesion between new and old concrete can be split into two different categories, namely: mechanical adhesion and Specific adhesion. This particular investigation will focus on the influences of mechanical adhesion between substrate and overlay in terms of substrate preparation, whereas the specific adhesion deals with chemical bonding and physio-chemical interactions (Silfwerbrand *et al,* 2011). The effectiveness of mechanical adhesion can be attributed to the rate at which the overlay penetrates the roughened surface of the substrate and after hardening, create an interlocking effect through cohesion. Figure 2.14 illustrates the different types of mechanical adhesion through bond failure.

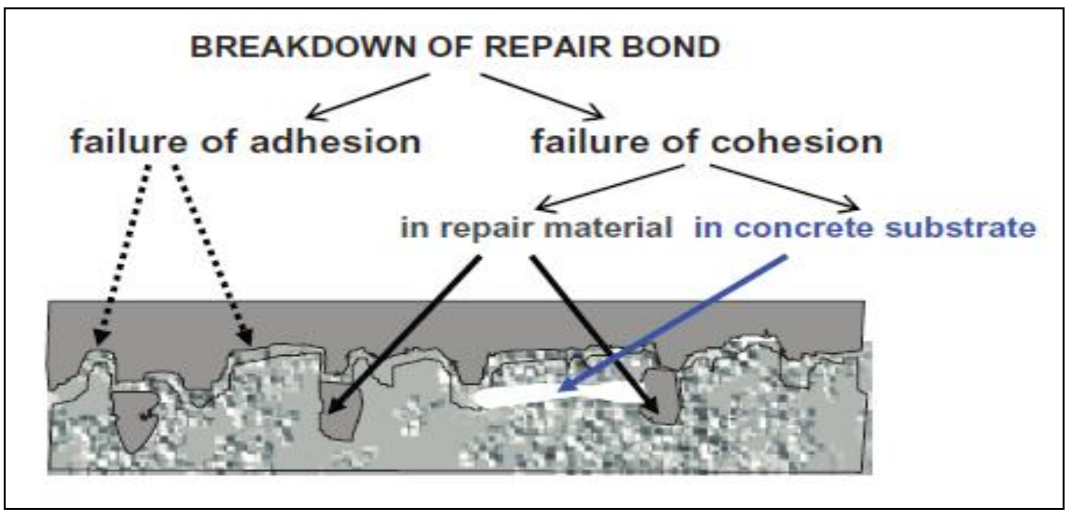


Figure 2.14: adhesion and cohesion failure (Czarnecki, 2009)

The mechanical adhesion experienced by the repaired specimen differs greatly between surfaces which are either in direct shear or tensile stress. For example, an increased surface roughness of the substrate will greatly influence shear bond strength, whereas tensile bond strength is primarily influenced by vertical anchorage achieved by the overlay within substrate pores and voids (Silfwerbrand *et al,* 2011)

2.6.4 Bond and factors affecting bond strength

When describing concrete overlays or concrete repair in general, the one common aspect which is always referred to is the bond between existing and new concrete. “Bond” is the connection of these two materials. The bond strength ultimately determines whether the repaired specimen will be able to successfully restore the concrete member to a satisfactory design life.

A good bond is paramount for the provision of a monolithic action in bonded overlay concretes. This allows for the repaired specimen to act as one entity rather than two separate materials (Silfwerbrand *et al,* 2011) However, the above statement is rather difficult to achieve, as there are many interlinking variables which may hinder the bonds strength if not accounted for. Below a detailed account of these variables are mentioned together with their level of importance.

2.6.4.1 Substrate roughening

As mentioned before the aim of concrete repair is to prolong the useful service life of an existing structure. Therefore, a prerequisite in achieving adequate composite action is lasting bonding between substrate and repair material. Surface preparation is often regarded as one of the main determining factors, whether a repaired concrete member is successful or not (Bissonnette *et al*, 2008). Surface preparation involves substrate roughening, moisture content and cleanliness. Bonding agents may also be used for substrate surface preparation.

Interface texture and roughness of the substrate concrete can improve the bond strength of the repaired concrete member if the procedure is performed in the right manner. The governing idea behind substrate roughening is to eliminate any weak or delaminated concrete from the substrate, without introducing micro cracks and provide a surface which promotes interlocking of the fresh concrete overlay and the substrate (Silfwerbrand & Beushausen, 2005). There are many roughening techniques available such as sandblasting, water jetting, wire brushing, flame cleaning, shot blasting and jack hammering (Julio *et al*, 2004). Figure 2.15 shows how the different mentioned roughening techniques, Jack Hammering (JH), Wire Brushing (WB) and Sand Blasting (SB) impact the surface of the substrate.

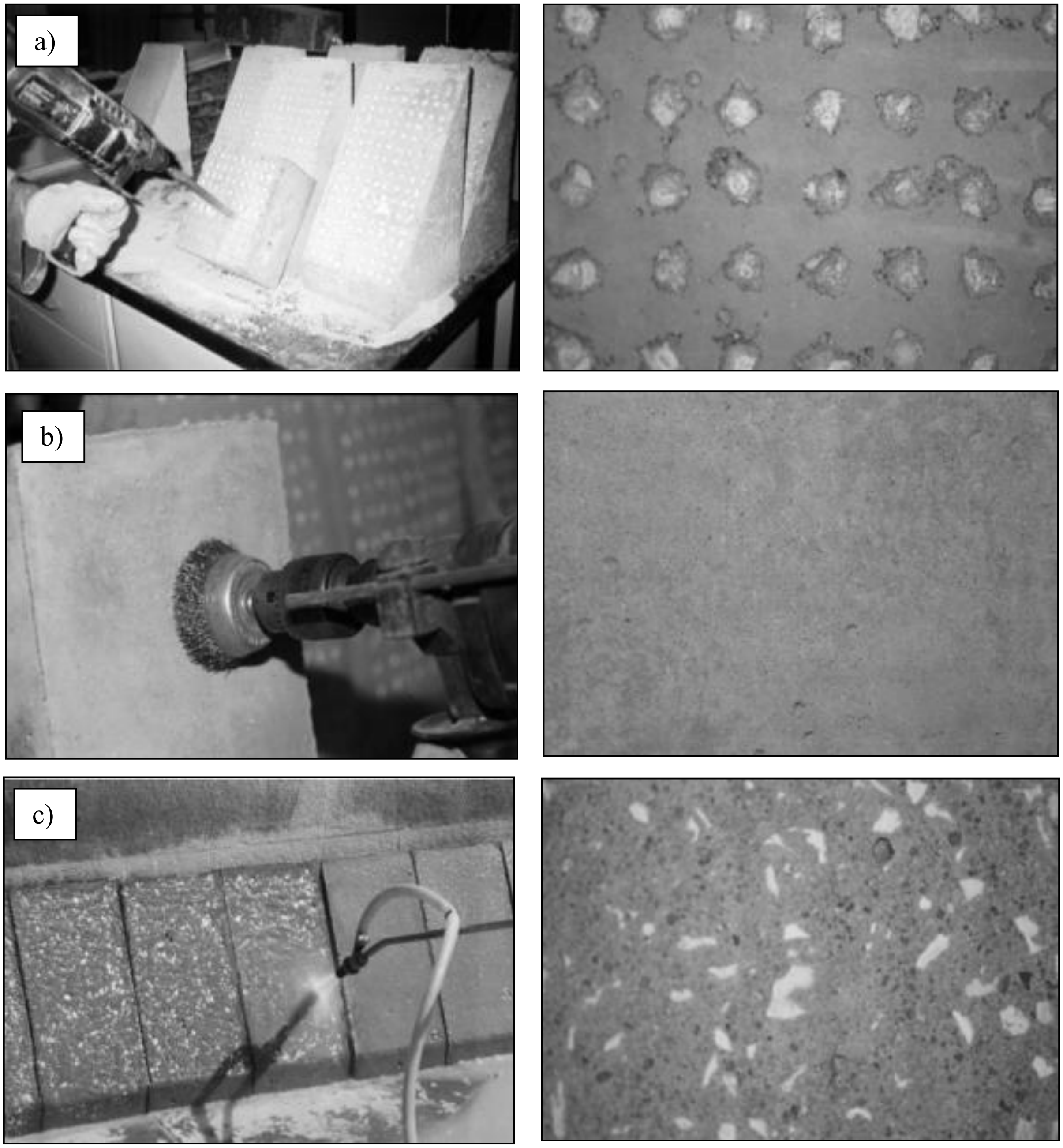


Figure 2.15: Substrate roughening, a) JH, b) WB, c) SB (Julio *et al*, 2004)

The substrate surface roughening techniques depicted above lead to different interface textures which help with the mechanical interlock between existing and new concrete. These interface textures can be split into three different categories: namely macroscopic texture, microscopic texture and sub-microscopic texture. Figure 2.16 illustrates the scale of the three different textures. The interface texture is commonly expressed in terms of roughness and largely depends on the substrate roughening method utilised (Bisonnette, et al 2012).

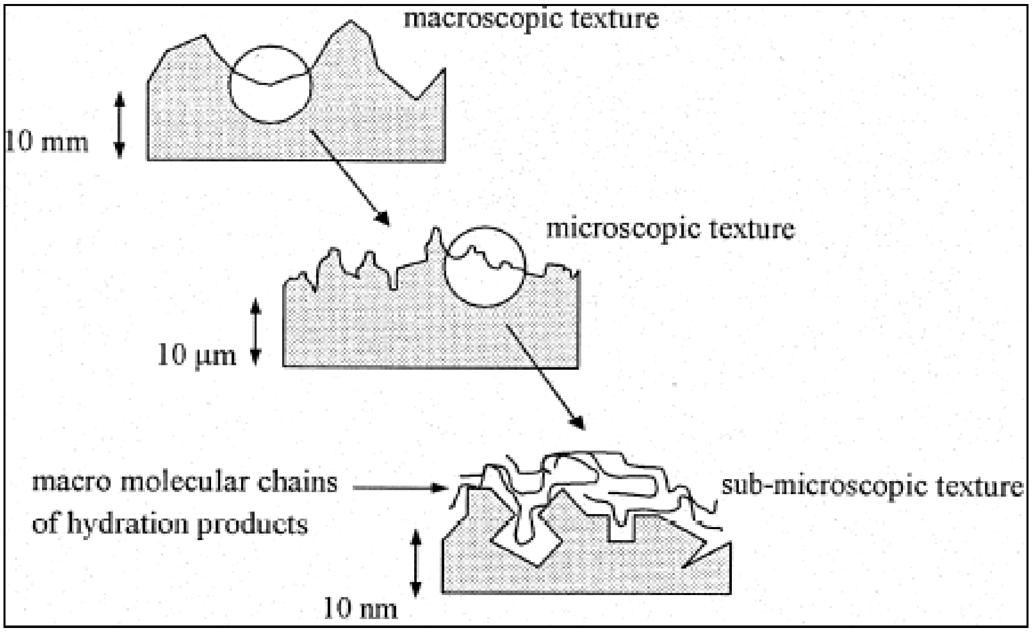


Figure 2.16: Surface textures of substrate concrete (Bissonette et al 2012)

According to Beushausen and Alexander (2005) and Bissonnette *et al* (2008) the sandblasting and water jetting technique for substrate roughening provide suitable results with regards to the bond strength of the repaired member without forming micro cracks within the substrate. As a result they are often the procedure utilized for concrete repaired members. To further indicate the influence of substrate roughening on bond strength, table 2.5 compares experiments performed by Bissonnette *et al* (2008) and Perez et al (2009). Both of the experimental testing utilised the pull off test for bond strength determination and implemented sandblasting (Sa), Scarification (Sc), Water jetting (WJ) and Jack hammering (JH).

Table 2.5: Comparsion of substrate roughening techniques

Interface treatment	Bond strength (MPa)	
	Bissonnette (2008)	Perez (2009)
Scarification (Sc)	2.45	2.60
Sand blasting (Sa)	2.60	2.40
Water jetting (WJ)	2.05	2.70
Jack Hammer (JH)	1.60	1.80

Although the bond values of the tested specimens are not identical when comparing the same interface treatment technique, they are very similar. The reasoning can be attributed to the different substrate composition and strength between experiments; however the main point which needs to be put across with respect to table 2.5, is the lower bond strength when jack hammering is implemented. This particular method provides are greater roughness coefficient in both studies; however the micro cracking which it imposes on the substrate counteracts the positive attributes which the roughened surface provides. Therefore, the provision of including a concrete substrate which is free from micro cracking is of paramount importance to the integrity of the repaired bond. Micro cracking creates a zone of weakness within the top layer of the concrete specimen and can negatively affect the bond strength (Bissonnette et al, 2008). The degree of micro cracking experienced by the substrate is governed by the selected method of concrete removal. Mechanical methods (hammers) will often induce micro cracks where as water jetting and sandblasting won't (Silfwerbrand *et al*, 2011)

To further justify the above statements, (Silfwebrand, 1990) provided a comparison between surface treatment with water jetting and jack hammering. The findings of the comparison are shown in table 2.6. The results portray a substantial increase in bond strength and consistency when moving from jack hammering to water jetting. However field studies performed by Talbot *et al* (1994) and Carter *et al* (2002) found that sand blasting after heavy mechanical concrete removal did eliminate the weak top layer of concrete containing all the micro cracks. This in turn resulted in a positive increase in bond strength. The only problem with this method is that there is an increase in cost and time, as you are effectively preparing the surface of your substrate twice.

Table 2.6: Comparison of substrate roughening techniques and bond strength

Interface treatment	Presence of micro cracks	All tests		Interface failures	
		Number of cores	Ave failure stress (MPa)	Number of cores	Ave failure stress (MPa)
Water jetting	No	16	1.86	1	2.23
Pneumatic hammers	Yes	16	1.10	5	0.94

Table 2.7 was adapted from Silfwerbrand *et al* (2011) and represents the different substrate roughening techniques available in the industry. The table includes both the weak and negative aspects of each technique together with its description.

Table 2.7: Substrate roughening techniques (Silfwerbrand *et al,* 2011)

Removal method	Principle behavior	Important advantages	Important disadvantages
Sandblasting	Blasting with sand	No micro cracking	Not selective, leaves considerable amounts of sand
Scrabbling	Pneumatically driven bits impact the surface	No micro cracking, no dust	Not selective
Shotblasting	Blasting with steel balls	No micro cracking, no dust	Not selective
Grinding (planning)	Grinding with rotating lamella	removes uneven parts	Dust development, not selective
Flame cleaning	Thermal lance	Effective against pollutions and painting, useful in industrial and nuclear facilities	Reinforcement may be damaged, smoke and gas development, Not selective
Milling	Creating longitudinal tracks	Suitable for large volume work, great bond results if followed by water flushing	Micro cracking is possible, reinforcement may be damaged, dust development, noisy
Pneumatic hammers	Compressed-air operated chipping	Simple and flexible use, large ones are effective	Micro cracking, damages reinforcement, poor working environment,
Explosive blasting	Blasting using small, densely spaced charges	Effective for large removal volumes	Difficult to limit to solely damaged concrete, not selective
Water jetting	High pressure water jet	Effective, selective, does not damage exposed reinforcement or concrete	Water handling, costs for establishment

One of the more simple and yet accurate ways of calculating the degree of roughness achieved from the above mentioned concrete removal techniques is the sand area method (Research and development division, 1989). A known volume (V) of sand is spread equally in a circular motion upon the concrete surface until all of the sand fills the surface cavities. The roughness factor (R_t) is measured in mm and can be calculated from the diameter (d) of the created circle, using the following equation:

$$\boldsymbol{R_t(mm) = \frac{4.V\ (mm^3)}{\pi.(d)^2\ (mm^2)}}$$ **Equation 7**

Figure 2.17 illustrates the concrete surface upon which the sand area method is applied. The procedure is simple and at least three measurements should be calculated on each surface to acquire a more accurate solution.

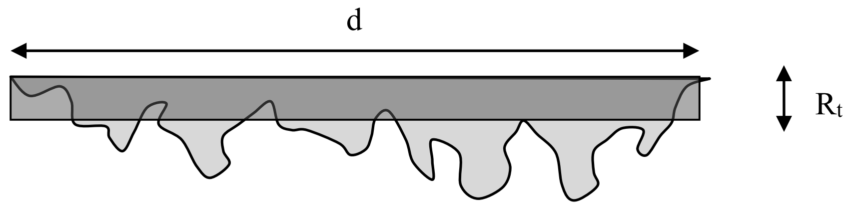


Figure 2.17: Sand Patch test method for substrate roughness

2.6.4.2 Moisture content

The moisture of the substrate concrete has been involved in many debates over the years with respect to whether pre-wetting the substrate surface actually plays an important role in bond strength, and what is the appropriate moisture content for the substrate to ensure that the bond strength is positively affected. According to Zhu (1992) and Silfwerbrand (2003) the moisture content does not play a major role in affecting bond strength of the repaired concrete specimen as long as there is no free water on the surface of the substrate. However, this view is in contrast to popular repair practices. Many engineers believe that concrete repair should be undertaken with a substrate which is in a saturated surface dry state. The problem is that the thinking behind this decision is solely based on engineering reasoning and not experimental results. The two views which engineers base their decision upon are as follows: Firstly, a dry substrate will absorb the water from the overlay material, resulting in the formation of a harsh mix which cannot provide a proper interlocking mechanism at the interface between overlay and substrate. Secondly, a substrate which has free surface water will tend to dilute the overlay mix resulting in the increase of the water binder ratio of the mix and decreasing the overlay strength (Beashausen & Alexander, 2009). The above two views is where the idea of saturated surface dry substrates originates from.

Beushausen (2010) tested the first view with regard to substrate moisture conditions and the experimental results strongly reconfirmed the results obtained from Zhu (1992) and Silfwerbrand (2003). The idea behind pre-wetting the surface of a substrate to a saturated surface dry state to improve bond strength is misleading, and in many instances, results in lower bond strengths between overlay and substrate. Furthermore Saucier & Pigeon (1991) provided experimental results which confirmed the above statement that free standing water on the surface of the substrate decreases the bond strength of the repaired specimen by a considerable amount. Therefore with the above mentioned, Silfwerbrand & Beushausen (2006) established a graph which best depicted previous studies carried out in this regard. Figure 2.18 illustrates how the percentage bond strength changes with respect to substrate moisture condition.

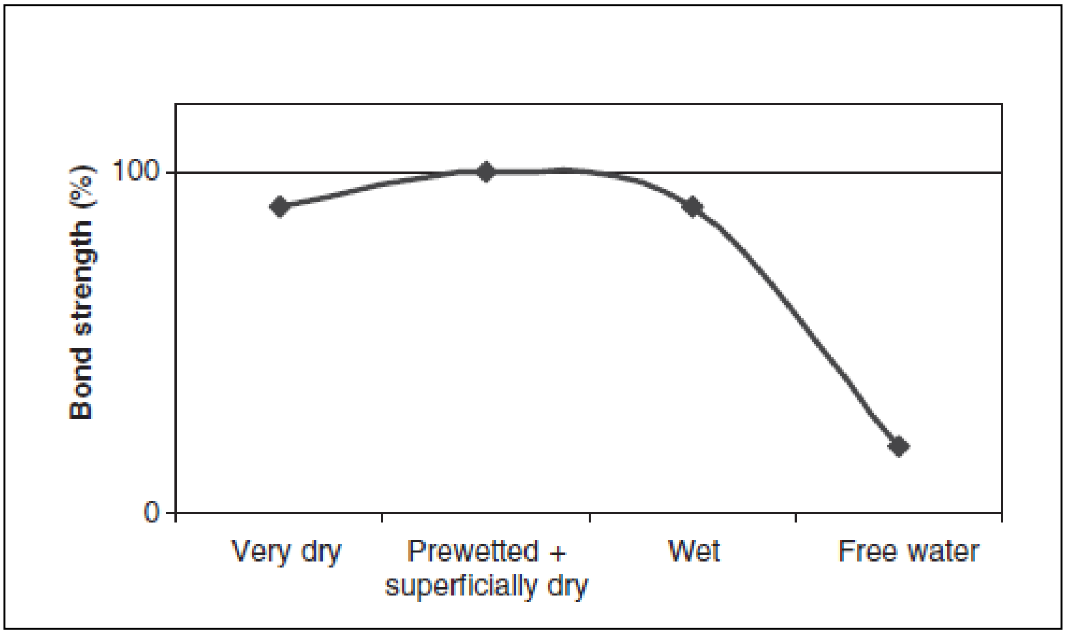


Figure 2.18: Moisture condition and bond strength (Silfwerbrand & Beushausen, 2006)

From figure 2.18 it is clear that there is no added benefit in subjecting the concrete substrate to pre-wetting when solely analysing bond strength. The added water can potentially disturb the interlocking capabilities of the substrate by limiting its capillary pore action with the overlay mix (Lukovic *et al*, 2012). However, concrete repair is often surrounded by compatibility issues and how the improvement of bond strength, for instance substrate moisture preparation in this regard, can often lead to the destruction of the bond through different concerns. In other words, although substrate pre-wetting may reduce bond strength to a certain extent, the imposed differential shrinkage between substrate and overlay due to excessive water lose in the overlay mix from substrate capillary action is of great concern. This differential shrinkage is reported to be the main attribute which lead to premature bond failure of repaired concrete (Martinola *et al,* 2001) and (Beushausen & Alexander 2007). Therefore, in an attempt to reduce this shrinkage engineers expose the substrate to saturated surface dry conditions. So, although a substrate which is in a SSD state may be beneficial in this point of view, the repaired bond strength may reduce. A substrate in a SSD state is a procedure to avoid further problems after casting than to try and achieve the most effective bond between overlay and substrate (Lukovic *et al*, 2012). One must keep in mind though that the experiments mentioned here were performed in laboratories where conditions are constant, whereas on site application is not managed as efficiently and may result in the application of the overlay on a substrate which has free standing water on the surface. Further investigation needs to be performed on the issue when comparing the benefits between added bond strength and induced differential shrinkage.

2.6.4.3 Bonding agents

Many engineers, without the proper understanding of the processes involved, specify bonding agents to improve bond strength between substrate and overlay of repaired concrete members. However, bonding agents are ineffective without the proper substrate preparation and can act as bond breakers if used incorrectly (Pigeon & saucier, 1992). To further investigate the appropriateness of bonding agents, Beushausen (2010) prepared a number of experiments in testing the usefulness of bonding agents in improving bond strength of overlays. Three different bonding agents were incorporated (two commercial products and one locally manufactured cement slurry). The results illustrated that a bonding agent only facilitates between the overlay and substrate, if the overlay mix is of a low workability. For high workable mixes (70 mm – 110 mm slump) the bonding agent has no substantial beneficial effect on bond strength.

These views by Beushausen (2010) further confirmed the results of tests experiments performed by Julio *et al* (2005) in which the effects of an epoxy resin bonding agent was investigated by performing a series of slant shear tests. The test method of the two mentioned authors differed; however Julio *et al* (2005) had similar concluding remarks: The application of the bonding agent provided no increase in bond strength when the substrate was exposed to surface roughening. Furthermore, the sandblasted substrate surface provided a greater bond than when the bonding agent was applied. Figure 2.19 provides a visual of the bonding agent application procedure prior to overlay casting.

Figure 2.19: Application of epoxy resin bonding agent (Julio *et al,* 2005)

Where bonding agents may provide a potential advantage, is not in increasing the bond strength itself, but rather creating a more consistent and reliable bond (Bissonnette *et al*, 2013). This is only true if the bonding agent is applied in a timely manner prior to casting of the overlay, and is often very difficult to accomplish on construction sites. Furthermore, with the different surface preparation techniques which have been development and are available today (mentioned above), the use of bonding agents are generally not required anymore to produce suitable bond strength (ACPA, 1990). If bonding agents are incorporated into the concrete repair process, then the compatibility of the bonding agent and the overlay mix and substrate must be considered.

2.6.4.4 Ridding damaged concrete; and cleanliness of substrate

Before a strong, durable bond between old and new concrete can be achieved, it is of paramount importance to rid the existing substrate of any damaged concrete. Silfwerbrand & Beushausen (2005) provide several reasons why it is necessary to remove the damaged concrete.

- Deteriorated concrete has low strength and leads to reduced load-carrying capacity.
- Deteriorated concrete can contain harmful substances such as chlorides, sulphates which may damage the newly applied concrete.
- Concrete which is damaged is relatively porous and promotes liquid/gas ingress.
- Reinforcement bars which have undergone corrosion attack need to be uncovered and cleaned from any rust.

The removing of deteriorated concrete leads to a substrate which is strong and relatively impermeable. The next step in the repairing procedure is to roughen the newly exposed substrate surface as mentioned previously in this section, followed by cleaning any leftover debris.

The cleanliness of the substrate directly influences the bond strength of the concrete overlay. A surface which is contaminated prior to overlay placement will exhibit poor bonding characteristics and premature failure of the repaired concrete member. Examples of poor cleanliness were portrayed by Silfwerbrand (1990), where Swedish bridges were repaired with the surface roughening technique of water jetting and bonded overlays in 1984 and 1985. Coring samples of the repaired concrete members illustrated week bonding as a result of poor surface cleaning after the water jetting of the substrate.

To ensure that contaminates of the substrate are removed from the substrate. The substrate should be cleaned twice – firstly directly after roughening of the substrate surface and secondly just before the application of the overlay either with high pressured water or vacuums (Silfwerbrand & Beushausen, 2005).

2.6.4.5 *Concrete overlay material properties*

Through extensive experimental research and development, the selection of different materials for bonded overlays has increased by a large extent. Not only does the client have the option of a conventional Portland cement mortar, but now there are repair mortars which can be customised to better suit the problem at hand. These bonded concrete overlays include:

- Portland cement mortar and concrete
- Silica fume mortar and concrete
- Polymer-modified mortar and concrete
- Steel fibre reinforced concrete
- Self compacting repair mortar
- Pre-packaged repair mortar and concrete

Although the above materials provide an indication on the progress of concrete repair, the increased number of repair mortars allows for a greater chance of premature bond failure if the appropriate procedures are not followed, and the overlay mix does not match the environment it finds itself in.

Compatibility considerations of overlay

In the past, the concrete repair profession performed their work under the principle "repair like with like" (Emmons & Vaysburd, 1993). The above approach was said to free designers from performing specific assessment tests customized to the problem at hand and guaranteed a durable bond between the old and new concrete overlay. Although the "repair like with like" approach sounds logical, the repair overlay and original material will not portray the same behavior over time. The overlay material when cast in ambient temperatures will undergo volumetric changes which are restricted by the presence of the old concrete. This will create internal stresses and strains which will ultimately lead to the cracking and debonding of the repair material (Bissonnette *et al*, 2013). Therefore the issues expressed in concrete repair must rather be addressed in terms of compatibility.

One of the ways to reduce the risk of repair failure is through dimensional compatibility. This determines the repairs ability to resist cracking and is influenced by the degree of restraint provided by the substrate as well as creep and shrinkage characteristics of the overlay. The interaction of these parameters will ultimately determine the material stress state and whether the tensile capability of the repair material is sufficient (Emberson & Mays, 1990). One way of achieving an increase in dimensional stability between old and new concrete, is by increasing the water/cement ratio and decreasing the paste/aggregate ratios. This will reduce the tensile strength of the mix, but at the same time increase the tensile relaxation and creep, with a reduction in elastic modulus. The net affect for the increase in w/c (within common ranges) has a positive result on the overlay cracking (Bissonnette *et al*, 2013). To further validate the above mentioned statement, Shin & Lange (2004) conducted experimental tests and analyses on potential debonding of the repaired material. They discovered that in a drying environment, high performance concrete (0.3 w/c) was more susceptible to bond failure. This was not the case for concrete overlays comprising of a w/c ratio of 0.4, 0.51 and 0.65.

Further concrete characteristics which need to be considered to achieve compatibility of the repaired member are permeability, electrochemical and chemical compatibilities.

Fresh material properties

The fresh repair material properties of the overlay are responsible for both early age strength development of the bond strength and bond durability (Silfwerbrand *et al*, 2011). The workability of the overlay mix together with compaction influences the ability to fill the open pore structure of the substrate and increase the effective contact area between the two composites of the repaired specimen. This will in turn create a strong mechanical interlock and hence increase the above mentioned bond strength and durability.

Although compaction is a prerequisite to maximise the benefits of the concrete overlays fresh material properties, this is often very tough to achieve on site where work conditions are not ideal. Very often workers are exposed to difficult application positions which hinder the compaction effectiveness of the repaired material. One way to avoid these negative implications is through the use of Self Compacting Concrete (SCC). Self-compacting concrete is not affected by the skills of the workers nor the tricky locations the concrete repair is carried out (Naderi & Ghodousian, 2012). This special concrete was developed in 1988 by Ozawa and is now being implemented in the engineering practice as concrete repair overlays. SCC consists of the same ingredients as normal conventional concrete such as aggregates, cement and water, with the addition of chemical additives. SCC does eliminate any inconsistencies with compaction; however the compatibility of the SCC with the concrete substrate must still be investigated with respect to dimensional stability.

To further explain just how important it is for the proper compaction of concrete figure 2.20 illustrates the relative stress gain achieved by the percentage of air voids present. This same concept can be applied to bonded overlays. The more air voids there are at the interface between substrate and overlay, the weaker the bond between the two, as the contact area is reduced.

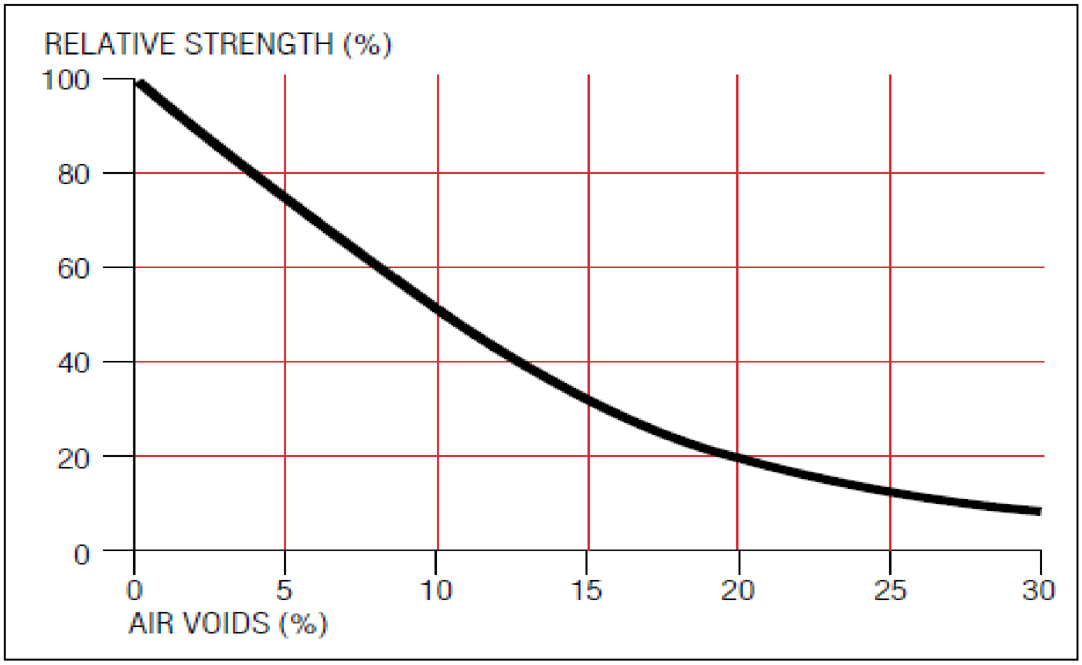


Figure 2.20: Influence of compaction (Cement concrete & aggregates Australia, 2006)

Hardened material properties

Many engineers believe that the strength of the bond between old and new concrete, is directly related to the compressive strength of the concrete overlay. Although the compressive strength does play a role, it is not that significant. However, the tensile strength is far more important with respect to bond durability, as this governs the ability of the overlay to resist volumetric changes (Silfwerbrand *et al*, 2011 bond). One way to ensure that concrete overlay has significant tensile resistance is to increase the early age strength development of the concrete mix. Delatte *et al*, (2000) found through experimental testing that this increased both tensile and shear bond strength considerably.

Another hardened material property of concrete which is concerned with concrete repair is permeability. The permeability of concrete structures indicates how quickly ions, liquids or gases can penetrate the concrete specimen. This characteristic of concrete is often related to durability concerns. The lower the permeability of the concrete the better suited the concrete is to resisting chemical factors which may lead to concrete deterioration. Often in harsh environments, concrete structures need to be designed to restrict the ingress of harmful substances. Therefore when repairing a concrete structure in this environment, special overlays are required. Tayeh *et al* (2012) investigated how ultra high performance fibre (UHPFC) concrete overlays reacted to a normal concrete substrate and if the bond strength between the two was appropriate. The results were promising and showed great bond strengths as well as improved durability in terms of reduction in the permeability rate.

However, there are a few downsides. Firstly, the use of UHPFC is very expensive and can be too costly if large remedial work is required. Secondly, the use of UHPFC may be too impermeable in relation to the substrate and thus prevent the moisture from the substrate to migrate through the bonded interface and into the overlay. This results in the build up of stresses at the interface which may lead to debonding (Schrader, 1992). Further investigation needs to be performed in this regard.

Furthermore, the addition of polymers to the cementitious repair mortar has a positive effect on the hardened concrete properties of the overlay and hence the repaired specimen as a whole, when subjected to varying temperatures (Atzeni *et al*, 1993). The polymers incorporated within the overlay mix have the ability to reduce drying shrinkage and hence decrease the stresses experienced by the interface (Silfwerbrand *et al*, 2011). Granju (1996) stated that the polymer increases bond durability through the control of crack propagation. Although the incorporation of polymers/fibres within the concrete overlay mix inflates the cost of repair. The increase in price is justified by the increase in the repaired specimen's performance.

The strength of the bond between new and existing concrete can also be influenced through the use of cement extenders. Abbasnia et al (2009) investigated how mix proportions of aggregate, w/c ratio and cement extenders influence the bond strength. The investigation illustrated that the use of smaller sized aggregates increases the free shrinkage of the overlay due to the decrease in the elastic modulus of the aggregate. Furthermore, incorporating silica fume (cement extender) into the mix does provide added bond strength. This is mainly due to the improvement of the interfacial zone microstructure.

2.6.4.6 Interfacial zone between repaired concrete

One of the more fundamental aspects of concrete repair and hence a question which has been investigated timorously over the past decade, is how does old and new concrete bond together. The understanding of the aforementioned allows engineers to develop repair strategies which best suit their unique problem at hand. Pigeon & Saucier (1992) investigated the bonding relationship between new and existing concrete and developed a theory indicating an interface zone between the two different concrete layers which is similar to the one found between aggregate and cement past. This interfacial layer described as a wall effect, promotes a zone of weakness (figure 2.21).

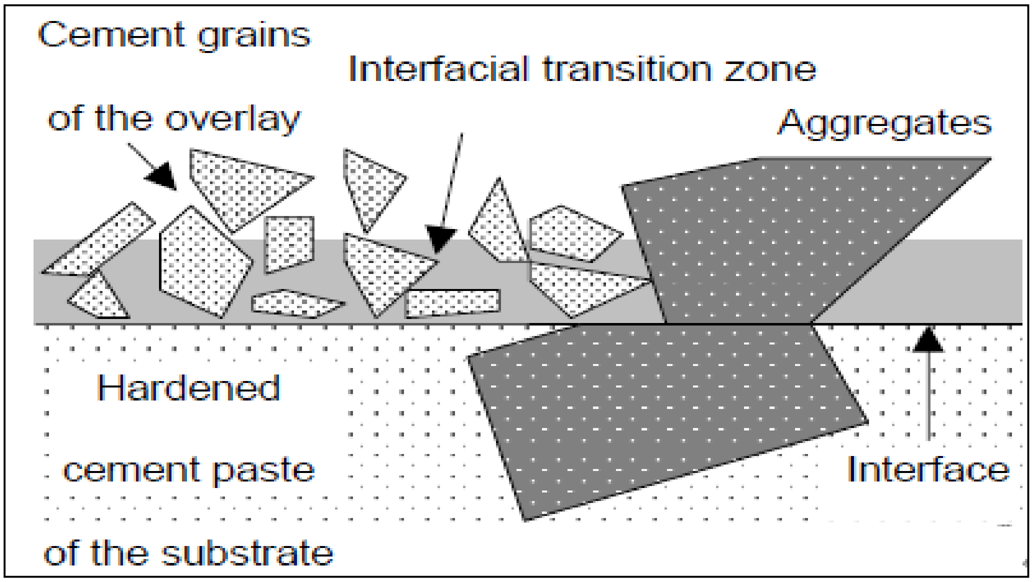


Figure 2.21: Interfacial zone between new and old concrete (Silfwerbrand *et al*, 2011)

A conventional uniform hardened concrete can be described as a three-phase composite system, comprising of the cement paste, aggregate and the interfacial zone between them (Al-Attar, 2013). Van Mier (1997) summarised existing knowledge on the interfaces between aggregate and cement past and illustrated that calcium hydroxide generally forms a boundary between them, followed by the formation of Calcium hydroxide crystals, ettringite and calcium silicate hydrate. This lattice structure promotes a high porosity in that particular region. Van Mier (1997) further indicates that the fracture location of concrete specimens generally exist marginally off centre between the boundary of aggregate and cement paste, found in the porous transition zone; Although the above mechanisms have not yet been fully investigated with respect to bonding new to existing concrete. Previous research performed does provide a certain degree of explanation behind the views of Pigeon & Saucier (1992). According to Silfwerbrand *et al* (2011), Beushausen (2005) found that interface failure between concrete of different ages often occurs very close to the interface, but within the overlay concrete. This was the case for both short and long term bonded concrete overlays (over two years), when tested with the direct interface shear method. This supports the mentioned theory of an interface zone between overlay and substrate as illustrated in figure 2.21

Due to the fact that the above mentioned interfacial zone between the substrate and overlay has been identified as the plan of weakness, researchers (Li, 2002), (Xiong *et al*, 2002) and (Kuroda *et al*, 1999) tested ways in which the interfacial zone can be modified in order to provide for stronger and more durable bonds. One of the suggested solutions was to apply additives or binders such as fly ash onto the substrate prior to casting in an attempt to modify the chemical composition of the interfacial zone. Kuroda *et al*, (1999) suggested that an increase in the effective bond strength at the interfacial zone depended largely on the SiO_2 and CaO contents of the additives. It must be noted that although larger amounts of SiO_2 are preferred, the presence of CaO also provided strong bond strengths and further reiterates how the interfacial zone can be modified even if the fly ash utilized consisted mainly of CaO and small quantities of SiO_2. The results of Kuroda *et al*, (1999) investigation are provided in figure 2.22.

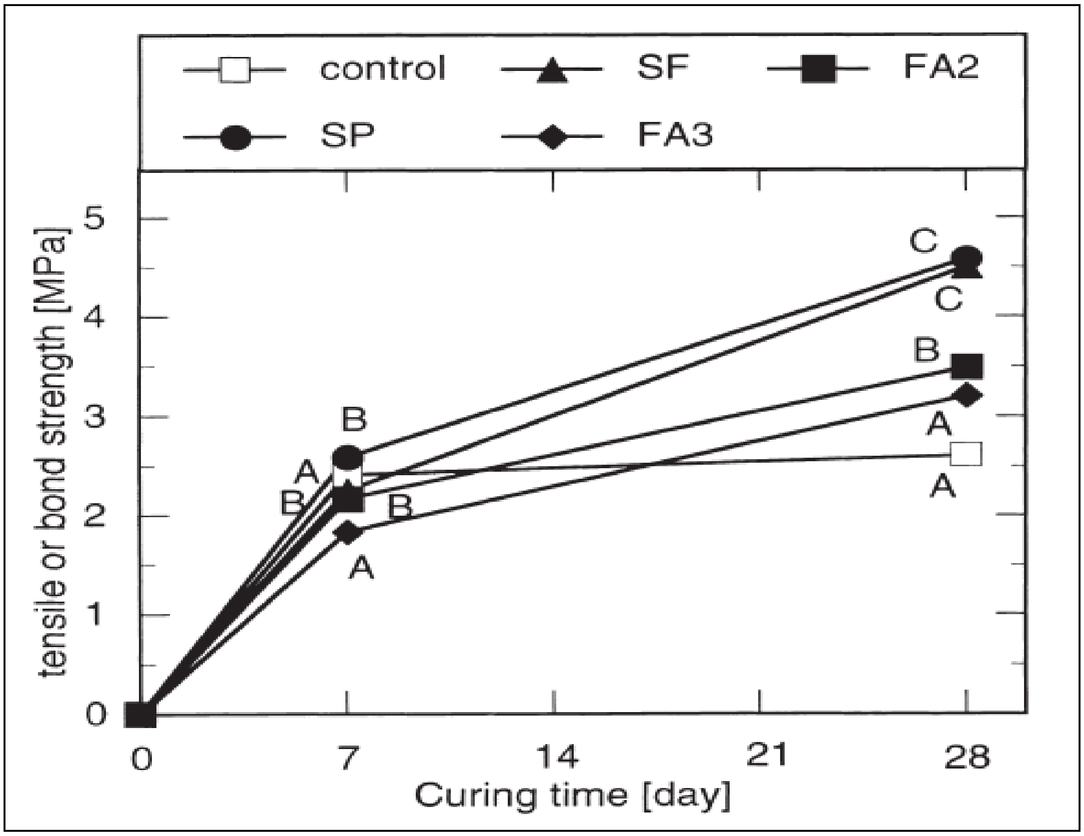


Figure 2.22: Addition of pozzalanic materials on substrate surface (Kuroda *et al*, 1999)

Here the direct tensile test was utilised together with five different materials which were placed on the interface prior to overlay application. These five materials were: the control (no interfacial material), Silica fume (SF), Fly ash (FA2 and FA3 – different types) and Silica powder (SP). The interface materials were prepared in the same manner with 0.38 of water-solid (cement and added material) mass ratio and 0.43 mass ratio of added material to Portland cement. From figure 2.22 it is clear that the added materials on the interface provided for a stronger bond strength when enough time was allowed for the full pozzalanic reaction to take place.

The results of the above investigation was confirmed when Li (2002) conducted similar experiments, but now implemented a shear splitting test to establish bond strength as well as altering the overlay concrete. Table 2.8 and 2.9 show the results for three different overlay concretes and four binders.

Table 2.8: Effects of binders on the bond strength at 28 days (Li, 2002)

	Binder type (MPa)			
Concrete overlay	Cement paste	Expansive binder	Fly ash mortar	Without binder
Fly ash	2.20	2.30	2.20	1.95
Portland	2.45	2.75	2.90	2.00
Expansive	2.70	2.95	3.00	2.00

Table 2.9: Effects of binders on the bond strength at 1 year (Li, 2002)

	Binder type (MPa)			
Concrete overlay	Cement paste	Expansive binder	Fly ash mortar	Without binder
Fly ash	3.95	3.70	4.40	3.25
Portland	3.80	3.70	4.20	3.20
Expansive	3.65	3.65	3.90	3.15

Although the expansive binder provided a great early age increase in bond strength compared to the other tested binders or lack thereof, as the age increased, the influence of the expansive binder decreased. The best results were established when the fly ash was incorporated in the binder. The interfacial zone of the repaired specimen was enhanced and therefore increased bond strength.

2.7 Testing procedures for bonded overlays

There are many existing tests which are available for determining the bond strength between the concrete overlay and substrate. These testing procedures can be split into several different categories, namely: tension, torsion and interface shear tests (Momayez *et al*, 2004). It is important to note that although there are an abundance of different test measures, the bond strength calculated is greatly dependant on the type of test measure utilised. Figure 2.23 schematically shows different test measures related to concrete overlays. While some of the proposed test methods are not popular on site applications, others such as the pull of test (A-B), shear test (D-H) and interface shear test (J-K) are very common methods for determining bond strength. A detailed description of the aforementioned is presented.

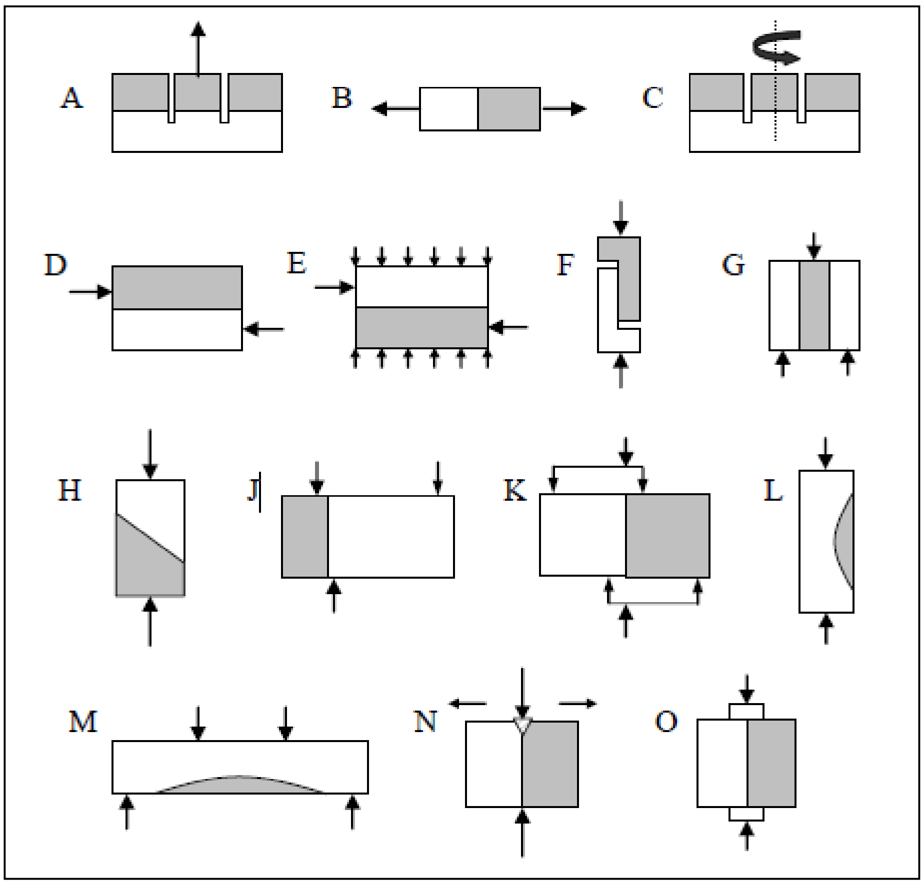
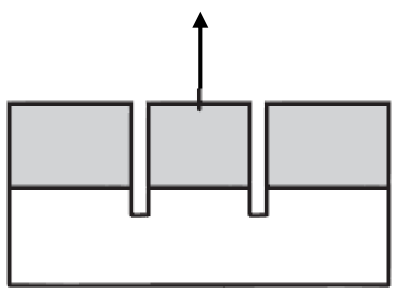


Figure 2.23: bond strength testing methods (Beushausen & Alexander, 2007)

2.7.1 Pull off tests

One of the most common test methods used for determining bond strength of a repaired member is the pull off test. This popularity is mainly attributed to the fact the test can be easily carried out on an existing structure or in the laboratory (Beushausen & Alexander 2007). The core pull off test is included in the proposed European standard for repair materials and involves drilling two cores through the repaired material and at a depth of 15mm into the existing substrate. A metallic disc is then glued on the upper surface of the core by means of a suitable epoxy adhesive and then pulled by a suitable tension machine (Austin *et al,* 1995). Figure 2.25 illustrates the on situ tension pull off test mentioned above.

Another simplified laboratory version of the pull off test is illustrates in figure 2.24 and requires the use of 150mm concrete cube moulds. This method involves casting a separate 75mm substrate and overlay mix in order to represent a repaired material. A metallic disc is then again placed in the centre of the cube and pulled apart by a tension machine until failure.



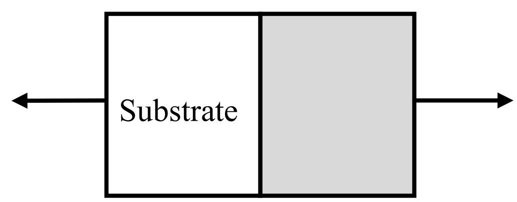


Figure 2.24: Laboratory pull off test using concrete cube moulds

Although the pull off tests mentioned above seems simple in its application, there a many instances where the experimental procedure may provide inadequate results. One of the more serious problems encountered is the development of eccentricities in the member due to the load application not being directly in the centre of the repaired member. These eccentricities often lead to a large scatter of results which does not accurately determine the bond strength between overlay and substrate (Beushausen & Alexander 2007). Furthermore, the pull off tests only provides an adequate determination of the bond strength of the material where the bond strength is less than the tensile strength of the concrete. Therefore this particular test measure provides a lower bound solution to the bond strength problem. This can be appropriate for determining the minimum bond strength required in the case of in situ control of concrete overlays; However in the case of determining the bond strength of repaired members by changing certain parameters, the pull of test is of little value. To further quantify the impact of applied eccentricities on the repaired member, Courard *et al*, (2009) developed an experiment where the repaired sample would undergo an applied angle of eccentricity of 2 and 4 degrees in order to establish the influence of small load eccentricities on the repaired member. Figures 2.26 and 2.27 illustrate the applied eccentricity either due to coring or application of load, where Table 2.10 shows the results obtained.

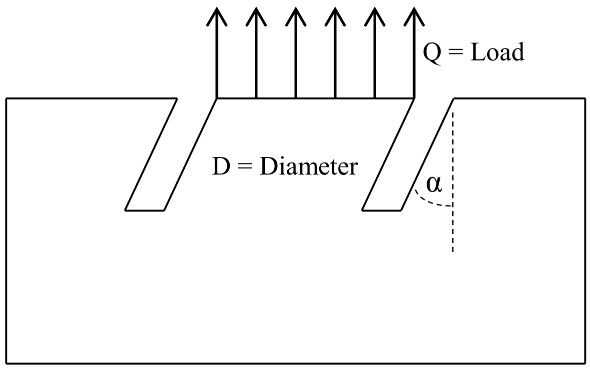


Figure 2.26: Inclination of coring

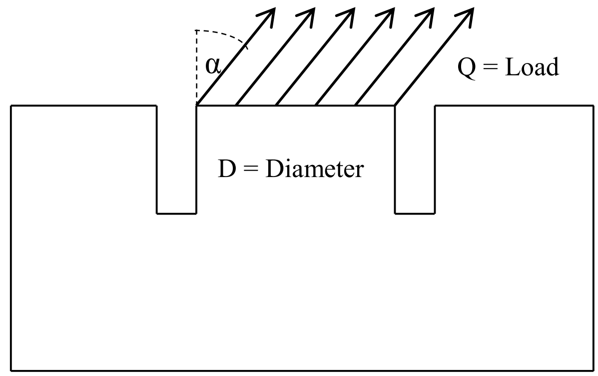


Figure 2.27: Load eccentricity

Table 2.10: Mean value of pull off strength (Courard *et al*, 2009)

	Core depth 15 mm			Core depth 30 mm		
Concrete Type	0°	2°	4°	0°	2°	4°
C30/37	3.7	3.4	3.5	3.1	2.9	2.9
C40/50	3.8	3.5	3.4	3.1	3.0	3.3
C50/60	3.9	3.8	3.4	3.3	3.1	2.9

From the table it is clear that the inaccuracies of either coring or load application can result in the reduction of strength due to an increase in stress at the bottom of the core. Courard et al (2009) concluded that the influence of load eccentricity and angle of inclination can be treated in the same way, as both produced similar stress distributions at the base of the core. The experiments showed an increase of stress of up to 9% for an angle of 2° and 19% for angle of 4°, with a core length of 30mm. For a core length of 15mm, the stress increased to 6% for an angle of 2° and 14% for 4° respectively.

Similar tests were performed by Cleland & Long (1997) which reaffirms the aforementioned, however the angle of inclination was far greater and resulted in a substantial decrease in pull off strength. Figure 2.28 illustrates the results.

Another interesting point to make with regards to the pull off test is that often the repair layer of a structure experiences a whole host of stresses which are primarily in the form of shear, whereas the pull off test is in pure tension. Therefore the test does not portray accurate site conditions. Nevertheless an appropriate gauge of bond strength can be obtained with this particular test method.

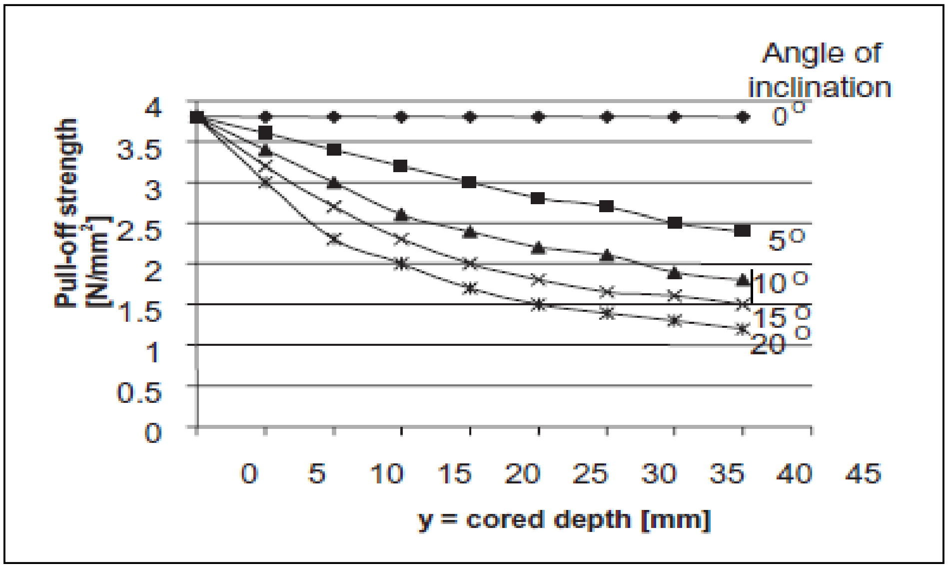


Figure 2.28: Influence of inaccurate coring on bond strength (Cleland & Long, 1997)

2.7.2 Shear testing

There are many different categories with regards to shear testing of repaired concrete members. There are those which impose pure shear onto the bond interface of the substrate and overlay such as the splitting prism or direct shear test, and shear testing which includes both a compression and shear component. The most common test procedure of this nature is the slant shear test (Momayez *et al*, 2005).

Slant shear test

This particular method was originally proposed in the form of the "Arizona slant shear test" (Kreigh, 1976) and was later developed and standardised in the British Standards (BS 6319 – Part 4, for testing repaired materials) as an appropriate way to calculate bond strength. The slant shear test either includes a square prism or cylindrical sample made of two identical halves which are bonded together at an angle of 60° to the horizontal. The sample is tested under axial compression and is exposed to both shear and compression stresses at the substrate/overlay interface (Momayez *et al*, 2005). The angle of the interface between new and old concrete was based on the universal compression test. In the compression test, the concrete specimen fails due to shear cracks along the inclined plane. This angle is generally between 50° and 70°. Therefore the slant shear test was based on this knowledge and tries to replicate this action by applying the interface angle at 60° and adding a compression force. Figure 2.29 illustrates the application of the slant shear test in order to calculate bond strength.

Although the slant shear test was fairly popular in the past for determining the bond strength of a repaired member, many researchers have found faults in the results obtained from the test procedure. This is mainly attributed to the high compressive stresses which exist in the slant shear test. These stresses impose large frictional forces which provide for better interlock between the substrate and overlay (Momayez *et al*, 2005) and (Beushausen & Alexander 2007). Thus the slant shear test provides an upper bond solution for bond strength. Furthermore, the test is relatively insensitive to surface preparation and roughness. Austin & Robins (1999), showed that although changing the roughness of the substrate specimen from smooth to rough does positively influence the bond strength, changing the method for acquiring a relatively rough surface and hence comparing different roughened surfaces, has no substantial influence on bond strength. The compression stress helps the interface to gain more friction and thus over powers the influence of surface preparation, unless the substrate is smooth.

In closing, the slant shear test is a simple and useful method for determining bond strength, provided that you are not altering the surface preparation of the specimen and understand how the compressive stresses interact with the interface.

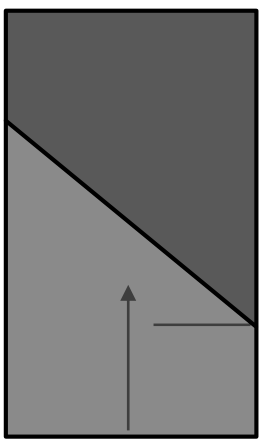


Figure 2.29: Mechanics of slant shear test

Figure 2.30: Slant shear test specimen

Direct shear tests

Over the years many different direct shear tests have been developed with the attempt to eliminate any eccentricities or tensile stresses applied on the bond interface. This would provide a better representation of the actual bond strength at the interface between substrate and overlay. Figure 2.31 represents the different direct shear tests according to Silfwerbrand (2003).

Figure 2.31 D) represents the common shear or mono surface shear test. This particular test method creates shear stresses directly at the interface between substrate and overlay in an attempt to try and find a true reflection of bond strength. Later, Pigeon & Saucier (1992) presented the "Modified Shear Bond Method" in an attempt to replicate typical on site conditions in the laboratory (figure 2.31 E). Due to the added compression forces applied to the top and bottom surface of the specimen, the bond strength increased substantially. The disadvantage with these two test measures is the creation of moments due to the applied shear force and their eccentricities. This generated moment, has the ability to distort true bond strength results.

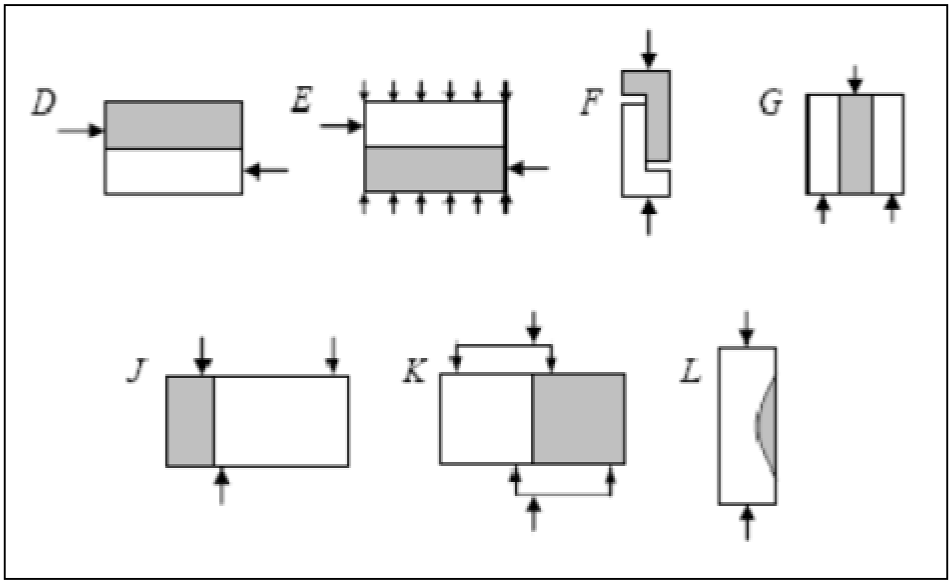


Figure 2.31: Direct shear bond testing methods (Beushausen & Alexander, 2007)

In an attempt to eliminate the undesired moments within the repaired member, researchers provided a solution known as the "Push-Out Specimen Method". This particular method, illustrated in figure 2.31 G), contained three forces which were applied in two different directions. The orientation of the forces induced no moment at the interface which could impact bond strength results (Chen *et al*, 1995). The only drawback for this particular method is that there are two interfaces within the member. Therefore the proposed condition is not a true reflection of a real case scenario. This made the test method difficult to analyse.

The Guillotine test was proposed in figure 2.31 J) and eliminated the problematic two face interface discussed earlier, as well as ensuring that moments due to eccentricities do not affect the bond of the repaired member. The third force is placed at a specific distance to minimise its magnitude and hence its effects on moment generation and the impact on bond strength.

Although the Guillotine test has many advantages, the testing specimen and setup is very irregular and requires the utmost precision when applying the third force. The direct shear or interface shear bond test in figure 2.31 K) is an attempt to simplify the Guillotine test. This results in a more accurate determination of bond strength between the overlay and substrate. Furthermore the test procedure is a fairly simple one and can make use of standard 150x150mm concrete cube moulds (Federation Internationale de la Precontrainte, 1978).

Figure 2.32 illustrates the interface shear bond test as performed in the laboratory, it is important to note that in order to eliminate the bending and tensile stresses within the bond interface, proper alignment of the apparatus is required.

Figure 2.32: Interface shear bond test

2.7.3 Comparison of Bond tests

From the above it is clear that there are many different ways in which the bond strength of a repaired member can be tested. However, the four bond tests which are internationally recognised and are trusted to produce results which represent a true indication of bond strength are: The tensile pull off test, splitting prism test, interface shear test and slant shear test. Momayez *et al* (2005), investigated how the bond strength between the aforementioned differed and if there were any relationships which could be established between them. Figure 2.33 indicates how the specimens were tested.

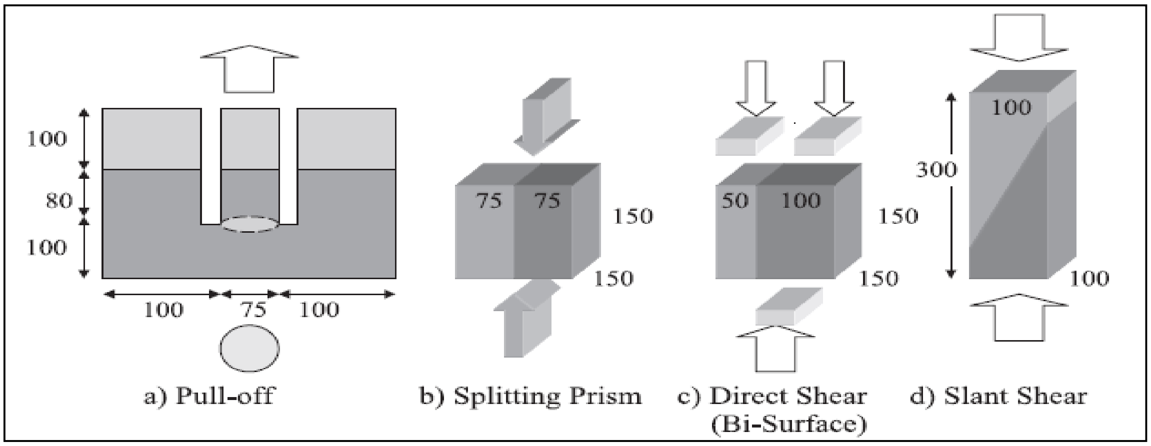


Figure 2.33: Dimensions of tested specimens (Momayez et al, 2005)

The results obtained showed that the bond strength decreased with the test method in the following order: Slant shear, interface shear, slitting and tensile pull off test. Figure 2.34 illustrates the above mentioned result. The tested concrete included percentages of silica fume (SF), polymer adhevise (K100) and Styrene butadiene resin (SBR).

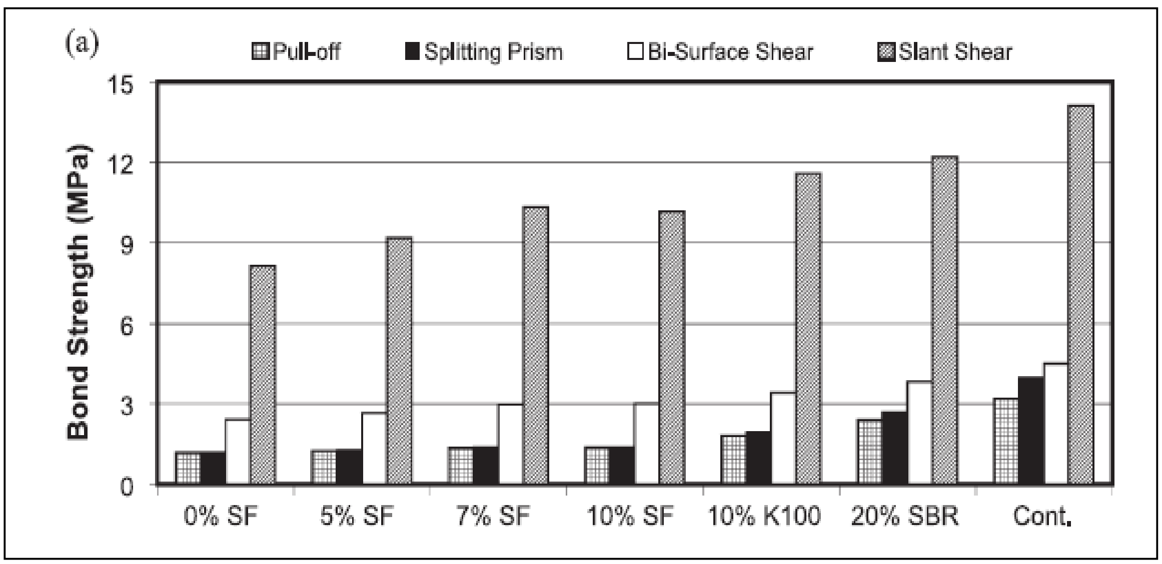


Figure 2.34: Bond strengths of different test measures (Momayez et al, 2005)

From figure 2.34 it is clear that, bond strength is highly dependent on the type of test method used. This is due to the type of stress which is being imposed on the bond. Due to the nature of concrete, bond is usually the weakest in tension and hence explains why the tensile pull off test recorded the lowest bond strengths in Momayez et al (2005) investigation. This is not to say that this is an inaccurate determination of bond strength, but rather that it is of paramount importance to ensure that the bond test selected represents the state of stress which the repaired member will be exposed to.

2.7.4 Other test procedures

Although the pull off and shear tests are one of the more popular laboratory experimental procedures for testing overlay bond strength. There are many other test procedures which include flexural and bending stresses in the interface bond zone of the repaired material for a more realistic loading application as one word expect in a particular structural scenario.

For the testing of torsional bond strength of a repaired concrete member, Silfwerbrand, (2003) developed an in situ testing procedure. The application is similar to the tensile pull off test; however instead of applying a tensile force on the member, a moment is applied. Another method for the testing of bond strength is in the form of fracture mechanics of the bond interface. This testing procedure is known as the wedge splitting device and characterises bonding of the substrate and overlay through crack opening, specific fracture energy and tensile interface strength in bending (Li *et al*, 1999).

2.8 Conclusions to literature review

2.8.1 Gaps in previous research studies

Although the bonded overlay technique has become a popular method with regards to concrete repair, many civil engineers still do not know the most efficient and effective way to carry out the procedure. With regards to the literature published, researchers have always isolated a particular mechanism which affects the bond strength of the repaired member; however, the interaction between these isolated mechanisms and other factors, is still not clear. An example is the interaction of moisture content of the substrate and mix properties of the overlay. Therefore in order to ensure that concrete repaired structures are durable and safe, one needs to relate all the different factors affecting the bond strength between overlays in an easy to read construction guideline.

2.8.2 Summary of literature review

Concrete is a universal material which is exposed to many different environments and loading parameters. As a result the concrete member may undergo damage with respect to physical or chemical processes. The extent and nature of the concrete damage often leads to the necessary action of concrete repair. Although there are many concrete repair methods, the more popular and inexpensive approach is the bonded concrete overlay technique.

The synthesis of the factors which affect the bond strength between the overlay and the substrate of the repaired member has shown that concrete repair is not as trivial as it seems. There are many factors such as substrate roughening, cleanliness, moisture preparation, curing techniques, mix properties of overlays and shrinkage problems to be considered. Each factor has the ability to completely undermine the repaired concrete member if not addressed. The main manner, in which the repaired member fails, is due to weak bond strength.

2.8.3 Summary of laboratory experiments to be performed

The laboratory experiments will model the behaviour of repaired concrete members using the bonded overlay technique, with the main objective to investigate the influence of substrate preparation on overlay bond strength. The experimental procedure utilised for determining bond strength was the interface shear bond test. The test specimens will include substrates with both different strengths and moisture contents. Furthermore the overlay mix will also vary in both strength and workability to achieve appropriate results for analysis. The idea behind the experimental procedures is to establish the governing factors which influence bond strength and how they relate to each other. From the experiments and analysis of the results, guidelines to the bonded overlay technique for concrete repair can be established.

3. Methodology of Investigation

3.1 Introduction

A considerable amount of progress has been made over the years in understanding the fundamentals of concrete composition and performance in both safe and harsh environments. Nevertheless, premature concrete deterioration is still very common in engineering projects and as a result, these particular structures require that repair and rehabilitation measures be implemented. One particular concrete repair measure which has become very popular in the engineering profession is the bonded concrete overlay technique.

The bonded concrete overlay technique increases the service life of structures by ridding the structure of damaged concrete (chemical and mechanical damage) and replacing it by a repair mortar which is suitable for the application it finds itself in, and at the same time providing a composite system between the new (overlay) and existing (substrate) concrete. The overlay concrete combines with the substrate to exhibit properties similar to what the initial concrete member represented.

Although this repair technique is very popular, there are still doubts in many researchers of how one can achieve the best bond strength between the existing and new repair material. Substrate roughening has been proven to increase this bond strength, together with substrate cleanliness. However, one of the more pressing issues is the impact of moisture preparation of the substrate prior to the application of the concrete overlay.

This investigation will challenge common engineering practice in the concrete overlay repair technique, that a substrate which is in a saturated surface dry state will provide a stronger bond between existing and new concrete. In order to achieve the necessary results for this investigation, three major experimental procedures needed to be carried out, namely: substrate preparation, overlay preparation and experimental testing.

3.2 Aim of research in view of selected parameters

This investigation aims to create a better understanding on how the fundamentals of substrate preparation (moisture condition) influence bond strength, together with different overlay properties. In order to provide valid results, many different parameters in terms of substrate and overlay composition, and moisture condition of the substrate were considered. The substrate which represents the existing concrete comprised of three different grades. The different grades were an attempt to portray common concretes present in South Africa and ranged from strong to weak. Each grade of substrate contained unique strength (50 MPa, 30 MPa, 20MPa), sorptivity and permeability values (see table 3.1). The inclusion of different substrates for testing was necessary to see if substrate composition altered how one needed to prepare the substrate in terms of moisture for better bond strengths. The substrates were sandblasted for surface roughening at an age of 28 days and left to mature for a further 90 days before overlay application.

The moisture conditions which were incorporated into this investigation included two wet conditions which represented a SSD substrate and two dry substrate surface conditions. Therefore, the three different substrates would each be exposed to four different moisture conditions prior to overlay application, in an attempt to quantify the influences of substrate moisture preparation. The measurement of the substrate moisture conditions is discussed in section 3.5.

The last parameter which this thesis investigates is how the strength and workability of a conventional concrete repair mortar may influence the overall bond strength of the composite specimen, with reference to substrate grade and moisture condition. Four different overlays were considered, with each varying workability (30mm and 120mm slump) and strength (25MPa and 40MPa). Upon the application of the overlay, the composite specimen was wrapped in plastic and placed in a room with a relative humidity of 50% and room temperature of 22 ± 0.5°C to cure for 28 days. The final composite specimen was then tested for bond strength using the interface shear test method described in section 2.7.

These moisture conditions together with the different substrate and overlay compositions provide the necessary parameters in which comparisons and decisions can be made with respect to bonded concrete overlays, with reference to how one should prepare the substrate surface with respect to moisture condition prior to overlay application, to achieve the strongest bond.

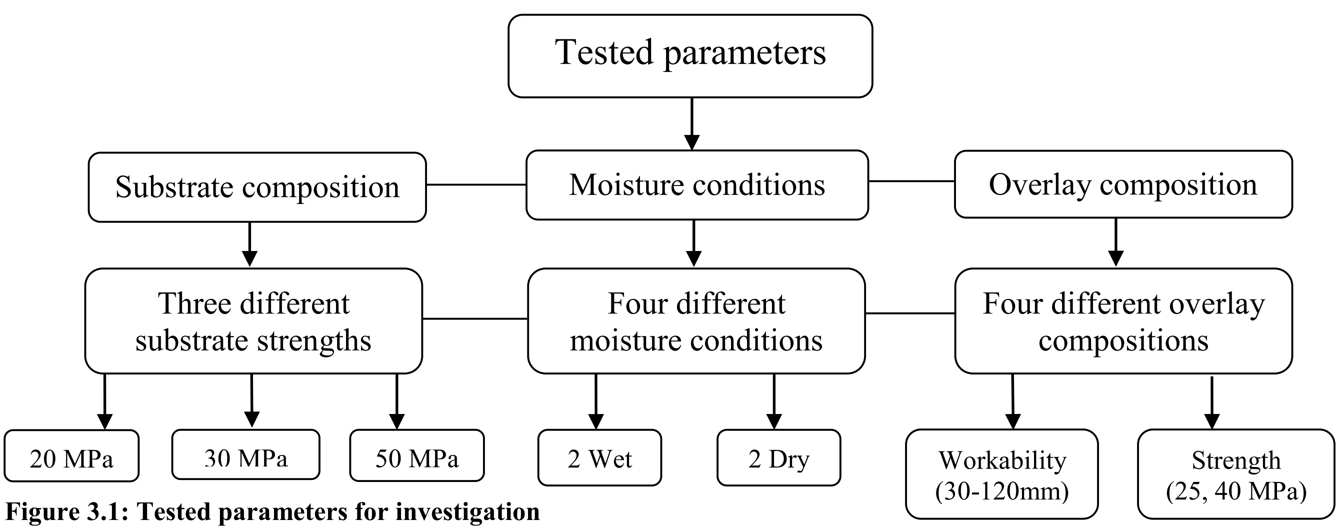


Figure 3.1: Tested parameters for investigation

3.3 Material properties

The concrete designed for the investigation comprised of both a course and fine grained aggregate, namely: Greywacke (coarse), and Philippi dune sand (fine) and Klipheuwel (fine). Both of the aggregates originate locally and are easily obtainable. In order to have a better understanding of how the materials will affect the concrete mixes, mechanical tests were undertaken.

The physical properties of the cement were obtained from the manufacturer's handbook. A summary of the properties is illustrated in appendix C, together with the sieve analysis of the fine aggregates.

3.3.1 Physical properties of aggregates

Four different aggregates were selected for the composition of the substrate and overlay concrete specimens, namely: 19 mm greywacke, 13 mm greywacke, Philippi dune sand and Klipheuwel sand. The sieve analysis of the different fine aggregates are represented in appendix C. It must be noted that during the casting of the repaired specimens, two different batches of Philippi dune sand were incorporated. The latter of the two batches was utilised for the concrete overlay design mixes.

Greywacke

Greywacke is an angular light grey aggregate, consisting of a mosaic of quartz, feldspar, mica, iron oxides and occasionally alumino-silicates (Grieve, 2009). The aggregate is also commonly known in the Western Cape as the Malmesbury shale. The 19 mm greywacke aggregate was used in the composition of the concrete substrate, whereas the 13 mm greywacke aggregate was utilised for the concrete overlay. Figure 3.2 illustrates the size difference between the two aggregates. No physical or chemical tests to characterise the aggregates with respect to composition and mechanical features (angularity, roughness) were performed on the 19mm or 13mm greywacke, as this was deemed not necessary for this particular investigation.

Philippi dune sand

The fine aggregate selected for both the substrate and overlay mixes was a round (non angular) light-yellow dune sand. Although the same dune sand was utilised for both substrate and overlay mix, two different batches were used. The first batch which was implemented into the concrete substrate mix designs was coarser than the second batch of dune sand. The sieve analysis graded the first batch of dune sand between 1.18 and 0.075

mm, and had a fineness modulus of 2.1; whereas the second batch was graded between 0.6 and 0.075 mm, and had a fineness modulus of 1.7.

The difference in mechanical properties of the two different batches did effect the water requirement of the concrete, as the finer the material the more water is required. However due to the fact that the differently graded dune sands were applied to separate stages in the concrete repair investigation (i.e. substrate and overlay) there was no inconsistencies in experimental concrete specimens.

Klipheuwel sand

Klipheuwel sand is a medium dense brown, gravely sand. The grading curves provided in Appendix C show Klipheuwel to be a well-graded sand, with grain sizes ranging from 2.36 to 0.1 mm and a fineness modulus of 1.7. The specific gravity of this particular fine aggregate ranges between 2.65 and 2.7. Figure 3.2 provides a comparison between the two different fine aggregates which the concrete substrate and overlay comprised of.

Raw materials: a) 19mm Greywacke, b) 13mm Greywacke, c) Klipheuwel sand, d) Philippi dune sand

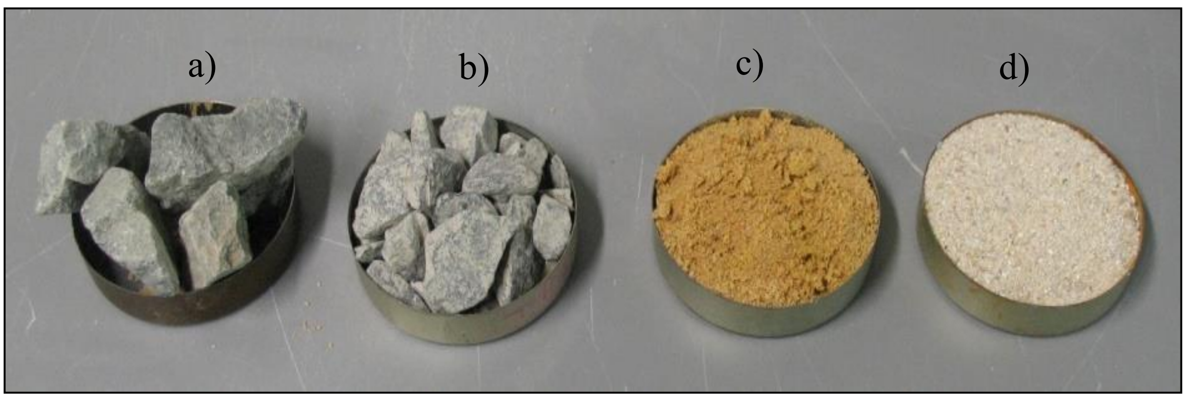


Figure 3.2: Comparison of raw materials

3.3.2 Cement properties

The cement applied to both concrete substrate and overlay mixes was a CEM I cement, namely the OPC 52.5N. The cement has a density of 3.14 kg/m^3 and a compacted bulk density of 1500 kg/m^3. It is made from high quality raw materials (i.e. first hand materials from mining), with the addition of gypsum to retard the setting time to approximately 80 minutes.

3.4 Research approach

The research approach adopted for this investigation comprised of both literature research and experimental work. The flow chart presented in figure 3.3 describes in detail the approach and scope of work performed, and how they are linked to one another to achieve a better understanding of the impact of moisture preparation on bond strength.

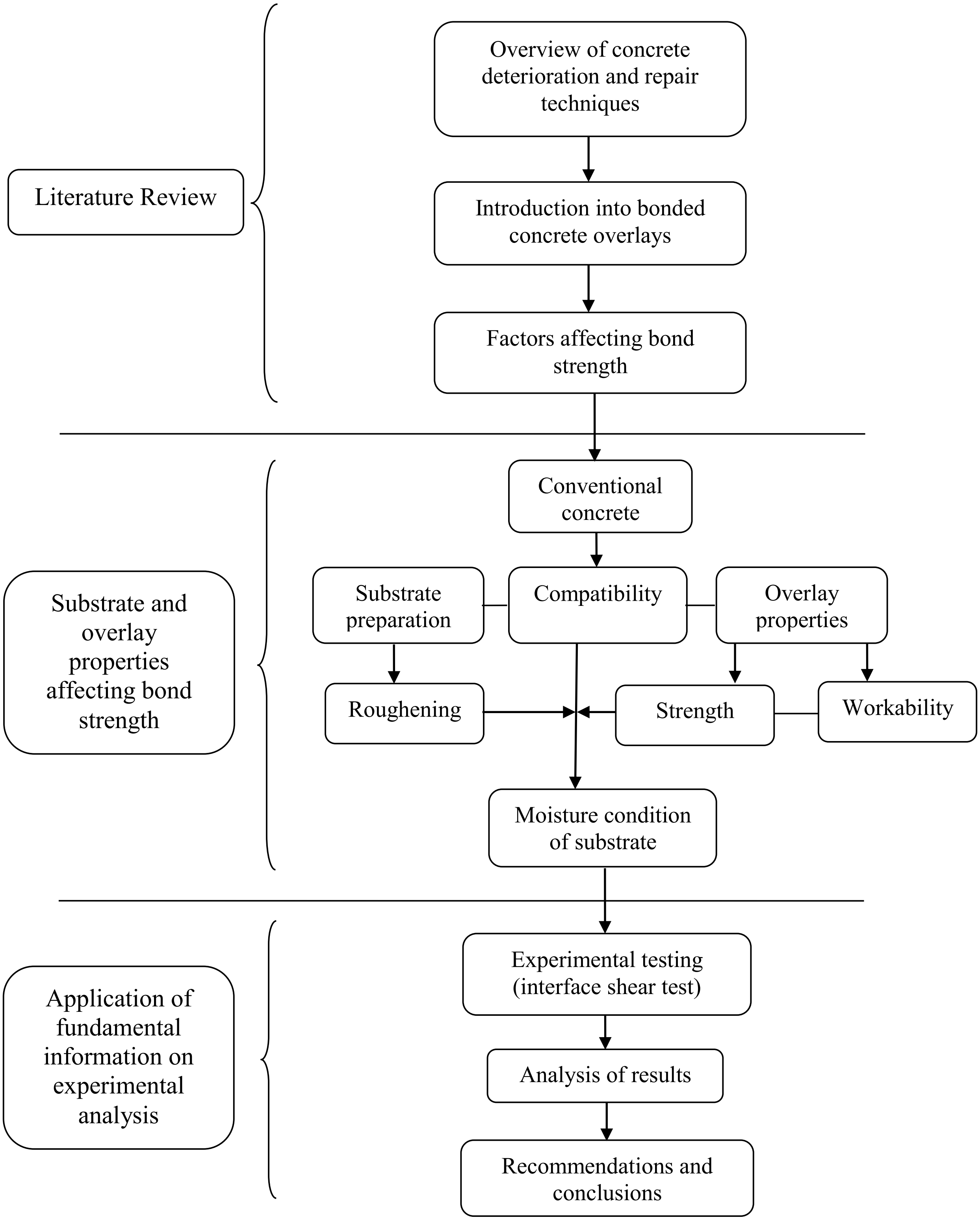


Figure 3.3: Research approach

The experimental work was split into three different categories or procedures as mentioned before (substrate preparation, overlay preparation and testing), with each requiring a suitable knowledge base as provided in the literature review in order to be completed in line with the primary objective of this investigation.

3.5 Substrate preparation

Concrete repair of structures is a very dynamic problem in the fact that there are many interlinking variables which influences repair performance, regardless of what repair technique is utilised. One of the elements which can impact the bond strength of the repaired concrete is the existing substrate. The substrate possess characteristics such as strength, sorptivity, permeability and surface roughness which can all affect the bond strength with the repair material (overlay) in both a negative or positive manner. This investigation aims at varying these characteristics to a certain degree in order to identify a relationship with the moisture preparation of substrate prior to the application of overlay and the overlay properties itself. A total of three different substrates were formulated, each with unique strength, sorptivity and permeability characteristics. Figure 3.4 illustrates the different stages within substrate preparation.

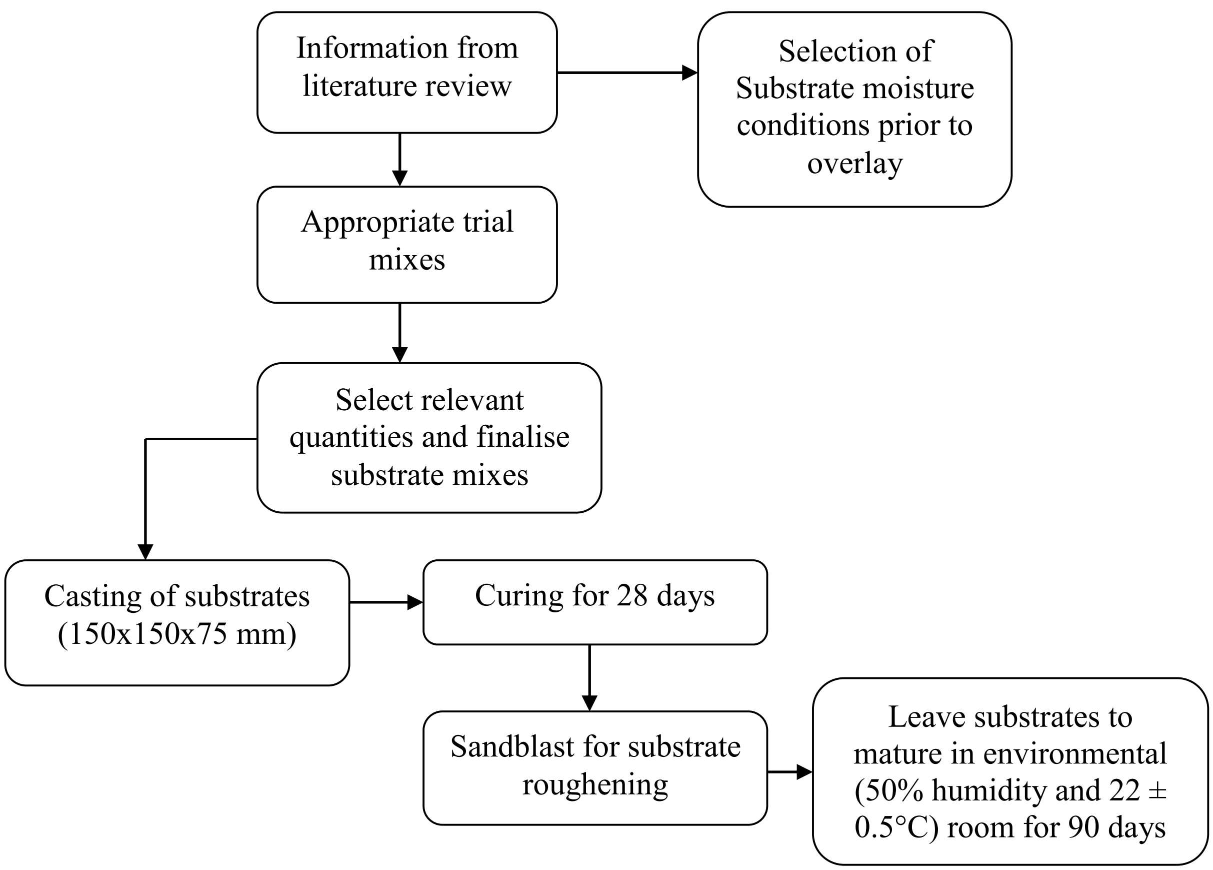


Figure 3.4: Substrate casting procedure

3.5.1 Substrate properties

Although the main objective of this investigation was to examine how substrate moisture preparation impacts the bond strength of concrete overlays, the concrete substrate properties them self also play an important role. For this reason a secondary objective was formulated in investigating how the strength of a concrete substrate together with differing overlay properties influences bond strength. Strength was utilised as a parameter as this could be adjusted according to the water cement (w/c) ratio of the substrate mix. High-strength substrates with a low w/c ratio are often relatively impervious and could restrict mechanical interlock between the substrate and overlay. Conversely a low strength concrete substrate comprises of a high w/c ratio and thus is fairly permeable and could assist in mechanical interlock between substrate and overlay.

For the above mentioned reasons, three different concrete substrates were formulated for this investigation: A high strength good quality concrete substrate (S1), a moderate strength concrete substrate (S2) and a moderate to low strength substrate (S3). In order to achieve the desired concrete substrates a series of trial mixes were made.

3.5.2 Substrate trial mixes

The concrete substrate was produced to portray three different strength grades with similar workability and composition. The strength grades allocated for the concrete substrate were 20, 30 and 50 MPa mixes. These mixes were finalised through trial mix designs and is shown in table 3.1, together with permeability and sorptivity characteristics.

Table 3.1: Substrate mix designs

Substrate properties	Substrate 1 (50MPa)	Substrate 2 (30MPa)	Substrate 3 (20MPa)
W/C	0.55	0.77	1.00
Water (kg/m^3)	192.5	211.8	230.0
CEM I 52.5 (kg/m^3)	350.0	275.0	230.0
19 mm Greywacke (kg/m^3)	1025.0	880.0	830.0
Phillipe Dune (kg/m^3)	840.0	1000.0	1020.0
Permeability			
Sorptivity (mm/hr$^{0.5}$) at 28 days	8.4	9.2	12.2
Porosity (%)	10.0	13.4	14.7

The substrate mixes were designed to be simple, yet realistic to everyday construction purposes. Therefore only one coarse and fine grained aggregate was utilised, together with the CEM 1 52.5N cement. The trial mixes were performed to check workability of the mix as well as 7 and 28 day strength. One of the key aspects which the substrate mixes were developed around in the trial mix design phase, was to ensure that the water content did not exceed 210 l/m^3, but at the same time allowing for the concrete to be fairly workable in the fresh state. Substrate 3 was an exception to the above as the mix was formulated to represent a poor grade of concrete which contained a great amount of cement paste in comparison to the coarse aggregate. The reason behind this decision was to investigate whether the added fines content within the concrete would negatively impact the mechanical interlock between substrate and overlay, for many structures in the past were constructed with similar concrete in South Africa.

Once the concrete mix designs for the three different substrates were finalised through the trial mixes, casting could commence. The sorptivity and permeability tests used to characterise the concrete, were performed according to UCT Durability Index Testing Procedure Manual (2009) and can be found in appendix D.

3.5.3 Substrate casting

As mentioned previously, the bond strength for the repaired specimens was tested with the modified direct interface shear test. This particular test method is both reliable and practical for the purpose of this investigation, and has been discussed in great detail in the literature review. Since the specimens consisted of a 150 x 150 x 75 mm concrete substrate and 75mm thick overlay, 150mm plastic concrete cub moulds were used for the substrate specimen preparation. This greatly simplified the casting procedure and allowed for consistent preparation of substrate specimens.

Since the plastic moulds were not going to be filled to capacity but rather to the desired 75mm, height markings were placed on each of the plastic moulds. After the substrate casting, the moulds were left to set in the labs for 24 hours after which they were de-moulded. The procedure for substrate specimen casting is described below.

Procedure: (substrate casting)

1) Prep all the plastic concrete cube moulds for casting and mix the measured ingredients while slowly adding the required water.
2) Once the concrete has been sufficiently blended, place the concrete into the concrete moulds and vibrate on the vibrating plate until the concrete reaches the 75mm mark.
3) Once the concrete substrates have been vibrated adequately and are 75mm high, they are placed in the environmental room for 24 hours for setting. The room was at a temperature of 22 (+/- 0.5) °C and relative humidity of 50%
4) After the 24 hour setting time, the concrete substrate specimens are de-moulded using the air gun and placed in the curing tank at a temperature of 27-30 °C for 28 days.

Apparatus: a) Plastic moulds, b) large scale, c) 50l mixer

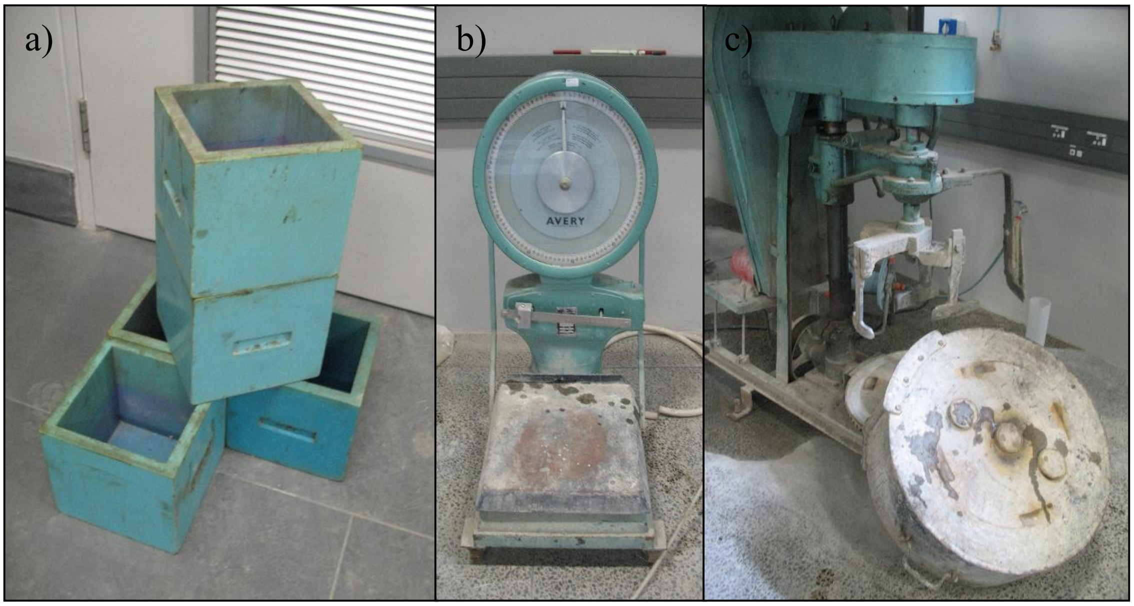


Figure 3.5: Apparatus for substrate casting

A total of 375 concrete substrates were cast, thus providing 125 substrates specimens for each of the three different mixes. The number of substrate specimens cast was governed by the number of variables which were to be tested. These included strength and moisture preparation of substrates, as well as overlay properties (workability and strength). A detailed description of the testing parameters is discussed further on in the thesis.

3.5.4 Substrate curing and surface roughening

As mentioned above, all substrate specimens were cured for 28 days and stored in the laboratory's creep room with a relative humidity of 50% and temperature of 22 ± 0.5°C for a further 3 months (90 days). The reason for the decision to rest the substrates for a further 96 days was twofold. Firstly, the substrates were representing the existing concrete of a structure and thus needed to be fairly mature. This allowed for maximum hydration and strength gain. Secondly, the 90 days created for a concrete substrate which would have undergone almost all of the drying shrinkage which may have influenced results.

Another aspect which impacts bond strength is substrate roughening. Over the past decade a huge amount of research has been conducted in this regard and is mentioned in the literature review (section 2.6.4.1). The surface roughening of the concrete substrates was an aspect which was kept constant throughout the three different substrate mixes (S1, S2 and S3). For this particular investigation sandblasting was utilised. Sandblasting provides a surface which is fairly rough without imposing microcracks which reduce the bond strength of repaired members. Although the three different substrate mixes composed of different strengths, the sandblasting rate was lowered with the strength grade of the concrete, in order to achieve a constant roughness coefficient for all three different substrates. This would allow for the comparison of results for not only a single substrate (i.e. moisture preparation and overlay properties), but all three in question. Figure 3.6 illustrates the three different substrates which have been sandblasted.

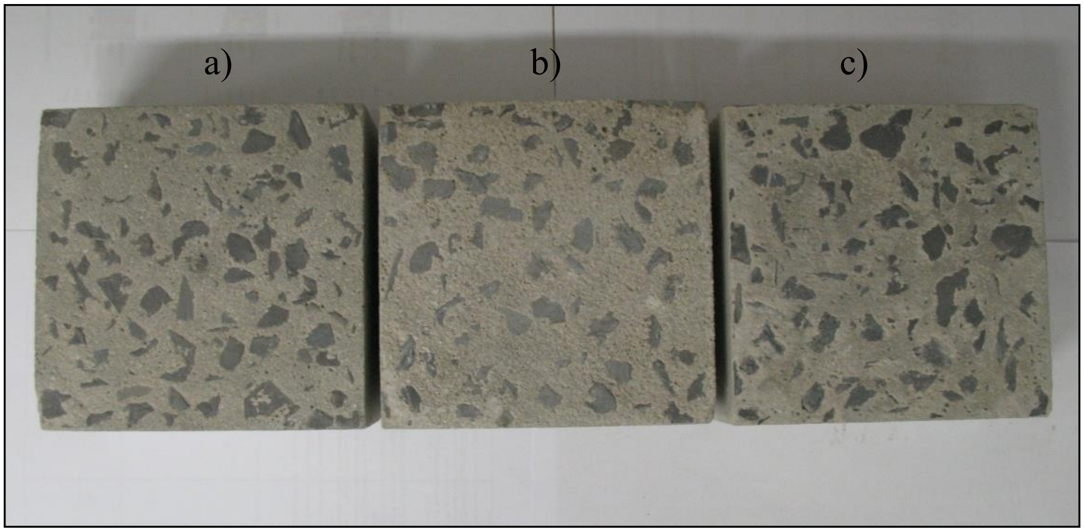


Figure 3.6: Concrete substrates a) 50 MPa, b) 30 MPa, c) 20 MPa

3.5.5 Substrate moisture preparation

The main objective for this investigation was to identify how the moisture preparation of the substrate will affect the bond strength of the repaired concrete specimen. Therefore four different moisture conditions were considered and are presented in table 3.2. From the table it is clear that the substrates were exposed to moisture conditions which are common on construction sites, but also represent extreme situations in order to provide a complete set of results.

Table 3.2: Allocated substrate moisture conditions

Substrate Moisture preparation		
No.	Description	Reference
1	Saturated Surface Dry for 24 hours	M1 - SSD24h
2	Saturated Surface Dry for 30 minutes	M2 - SSD30m
3	Ambient Room Temperature (creep room)	M3 - RT
4	Oven Dried at 50°C for 24 hours	M4 - OD24h

Prior to casting of the overlay, the substrate would have either been exposed to a SSD state, or represented a surface which was dry as in the creep room for at least seven days or oven dried at a temperature of 50 °C for 24 hours (after oven drying, the substrates were placed in the environmental room for 24 hours in order to cool and reach room temperature before overlay application). The substrates which were in the saturated surface dry moisture condition were placed in the laboratories curing tanks for a total of either 30min or 24 hours. Timers were used to ensure that the substrates experienced the same conditions throughout the laboratory experiments with regards to wetting and oven drying. A physical “touch” method was implemented in order to ensure that the substrate was in a SSD condition prior to overlay application. Every minute after the substrates were removed from the curing tanks, the moisture condition was checked by placing your hand on the surface of the substrate and removing it to see if any moisture remained. If moisture remained on your hand the substrate was still too wet for overlay application. The substrates were also cleaned to rid any accumulated dust particles on the surface before the moisture conditions were applied and after oven drying.

The above measures which were undertaken ensured consistency throughout the moisture condition application process and eliminated any redundancies which may have been accustomed to its application. Once the substrate was exposed to the appropriate moisture condition, the concrete overlay was applied.

3.6 Overlay preparation

Bonded concrete overlays have become a widely used tool for either repairing or strengthening concrete members, and in many instances are used to increase the service life of the structure which they are applied to. Although the conditions of the substrate (existing structure) do influence the bond strength and effectiveness of the bonded overlay, the properties of the overlay concrete mix are also of great importance to ensure a strong bond. Below is a detailed description of the overlay properties for the mix designs and reasoning as to why they have been included, together with overlay casting and curing procedure. Figure 3.7 provides further detail on the overlay application procedure.

3.6.1 Overlay properties

As mentioned in the literature, the overlay properties have a great effect on bond strength of the repaired member. For this reason a further secondary objective was formulated to find relationships between the strength and workability of the overlay, together with the moisture preparation of the substrate. These specific parameters of the overlay can be easily varied by altering the w/c ratio of the mix, as well as the fine and coarse aggregate content. The workability of an overlay mix may have the ability to either increase or decrease the bond strength between overlay and substrate. A highly workable mix could fill all the pores in the underlying substrate, creating a strong mechanical interlock; whereas an overlay mix which is very stiff may be restricted in filling the pores of the substrate and thus provide no mechanical interlock between the substrate and overlay.

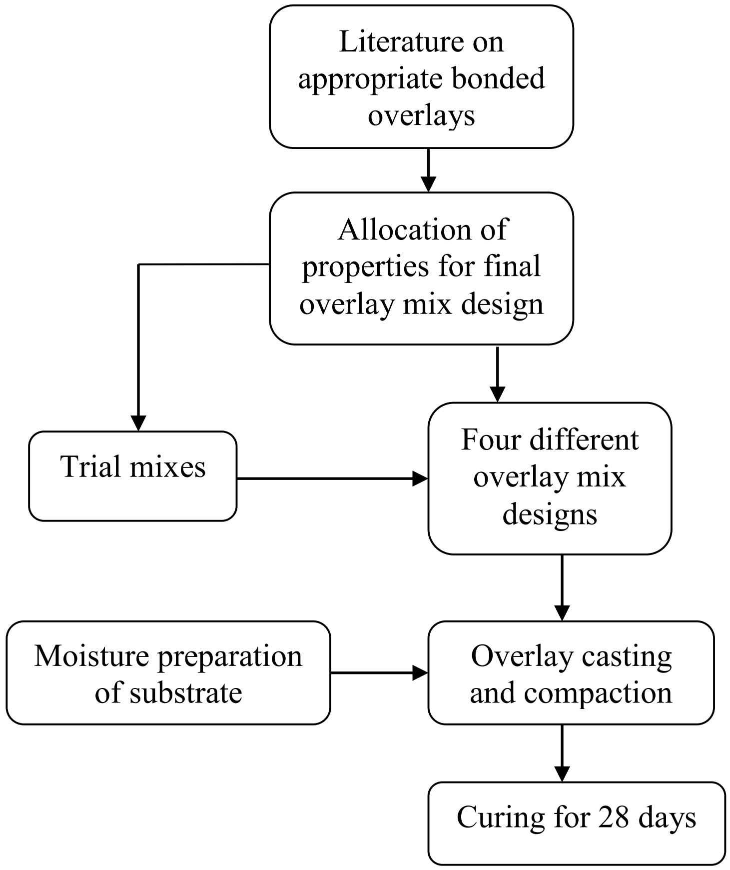


Figure 3.7: Overlay design and casting procedure

The above considerations for the concrete overlays were taken into account by formulating four different overlay mixes, namely: O1a, O1b, O2a and O2b. The number represents the strength grade, whereas the letter represents the slump of the mix. Table 3.3 shows the four different overlay mixes. To achieve the desired results for the different overlays, a series of trial mixes were made.

Table 3.3: Concrete overlay mix properties

Overlay concrete repair mortar properties				
No.	Description	Strength (MPa)	Slump (mm)	Reference
1	High strength and stiff repair mortar	40	30-40	O1a
2	High strength and workable repair mortar	40	120-130	O1b
3	Moderate strength and stiff repair mortar	25	30-40	O2a
4	Moderate strength and workable repair mortar	25	120-130	O2a

3.6.2 Overlay trial mixes

When repairing existing concrete members, there are many factors one might need to take into account in order to achieve a strong bond between the overlay and substrate. However the most fundamental aspect of the repair procedure, which is often neglected, is to ensure that the repair material is compatible with the existing concrete. This was one of the main focuses when developing the overlay mixes, together with altering the strength and workability to achieve the desired results. The four overlay mixes comprised of two different strength grades (25 and 40 MPa) as well as two different slumps (20-30 and 120-130 mm). The final mix designs for the concrete overlays are presented in table 3.4.

Table 3.4: Concrete overlay mix designs

Specimen	O1a	O1b	O2a	O2b
Cement CEM I (52.5N): kg/m^3	285	310	200	220
Water: kg/m^3	180	195	180	195
Greywacke 0-13 mm: kg/m^3	960	970	1000	1035
Sand 0-2 mm: Dune kg/m^3	495	455	505	455
Sand 0-2 mm: Klipheuwel kg/m^3	495	455	505	455
w/c ratio:	0.63	0.63	0.9	0.9
Slump (mm):	20-30	120-130	20-30	120-130
28-day design strength: MPa	40	40	25	25

The concrete overlays were developed with the same core materials as the concrete substrate. This included the CEM I 52.5N cement, as well as the Philippi dune sand. Where the mixes differed was in the inclusion of a finer yet identical coarse aggregate (Philippi dune sand) and by adding Klipheuwel sand in a 50/50 ratio with the dune sand. The inclusion of the Klipheuwel sand was to ensure that the required slump for the overlays was met without using superplasticisers or an excessive amount of water (i.e. greater than 200l/m^3). This ensured that the overlay was compatible with the substrate in terms of materials utilised, but at the same time being sustainable (i.e minimising water and cement usage). The trial mixes were performed until all the design requirements in terms of strength and workability, as mentioned in table 3.3, for the overlay mixes were met. To check the requirements, concrete workability and 7 and 28 day strength tests were performed.

The completion of the trial mixes allowed for the casting of the overlays to commence. The overlay casting procedure was far more complicated than that of the substrates. For instance, new moulds needed to be made, the substrates had to be prepared (moisture) before the overlays were cast on top, and manual compaction was required (refer to section 3.6.3).

3.6.3 Casting of overlays

The casting of the concrete overlays included a number of different steps in order to achieve the final composite member. Great care needed to be taken not only in the casting of the overlay, but also in the moisture preparation of the substrate. The final repaired specimen would have the dimensions of a 150 mm concrete cube, with the substrate and overlay both being 75mm thick.

A total of four wooden concrete cube moulds comprising of 18mm marine plywood were developed for overlay casting, with each having a carrying capacity of six concrete specimens. However before the wooden moulds could be utilised, they needed to undergo a series of waterproofing treatments. This would ensure that the wood did not absorb any of the moisture present in the substrate, which could falsify results. The marine plywood was coated three times with a deep penetrating waterproofing product. The design of the wooden moulds is illustrated in figure 3.8.

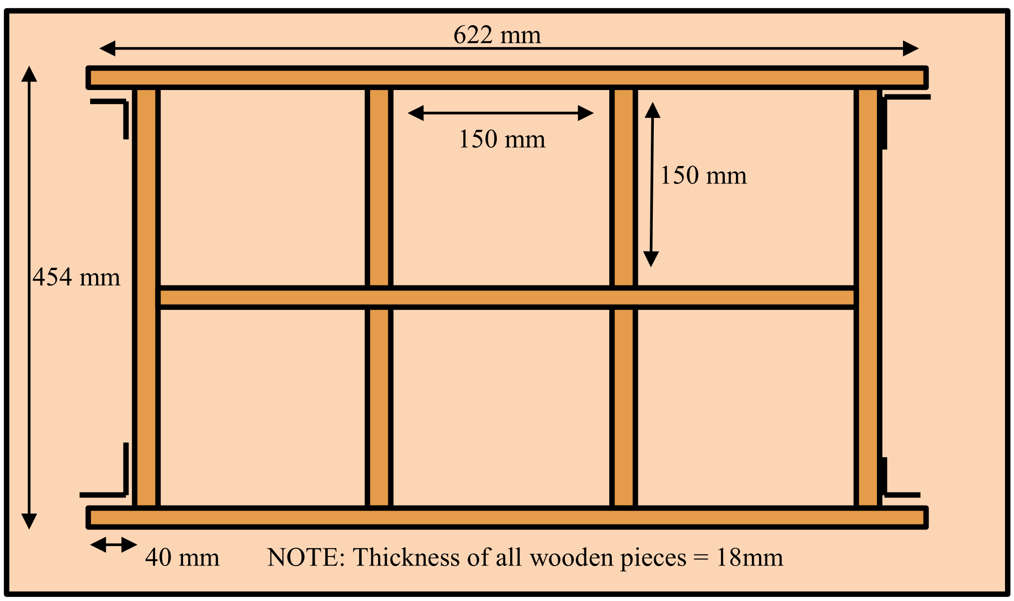


Figure 3.8: Plan view of wooden concrete cube moulds

One advantage which the wooden mould provided was the quick assembling and stripping time before and after casting. This allowed for an optimum amount of 24 specimens to be cast a day. Figure 3.9 and 3.10 illustrate how the wooden moulds were assembled.

Figure 3.10: Assembling of concrete cube moulds

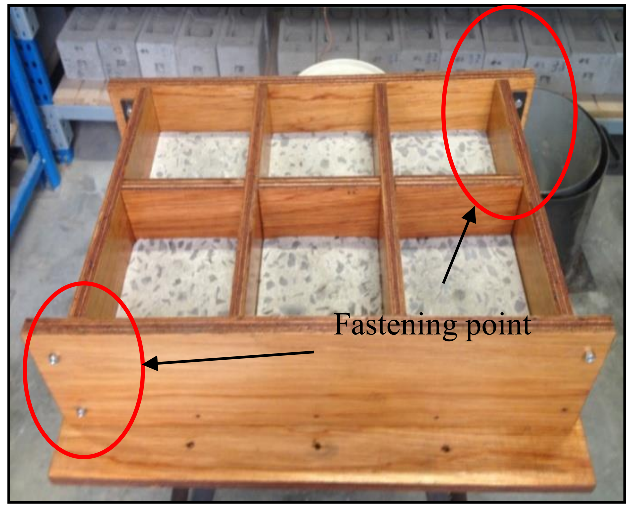


Figure 3.9: Fastening of wooden boundaries

1 → Set the wooden base in an appropriate location to provide stability, support and a level working station for the concrete specimens.

2 → Once the base has been levelled, place the wooden dividing centre piece on the base at an equal distance from all edges of the wooden base.

3 → When the concrete substrates reach their desired moisture condition, place them individually within the dividing centre piece. The concrete substrates are firstly placed in the middle compartment followed by the ends.

4 → Once all of the substrates have been placed within the wooden centre piece, attach the two end pieces (one wooden end piece includes a long and short end) and fasten them in a diagonal manner. Ensure that the wooden moulds are fastened tight enough to create a 'snug' fit with the concrete substrates.

Once the moisture conditions of the substrates were prepared, the overlay casting procedure was straightforward. All that was required was to manually compact the mix in three different layers. Manual compaction was utilised instead of the vibrating plate due to practical issues. Each layer received an equal number of 50 blows from a steel compactor (10 on each side and 10 in the middle of the mould). The compacting tool is illustrated in figure 3.12, with figure 3.11 illustrating the manual compaction process. For consistency of application, all of the first layers of overlays were cast and compacted before moving onto the second and third layer.

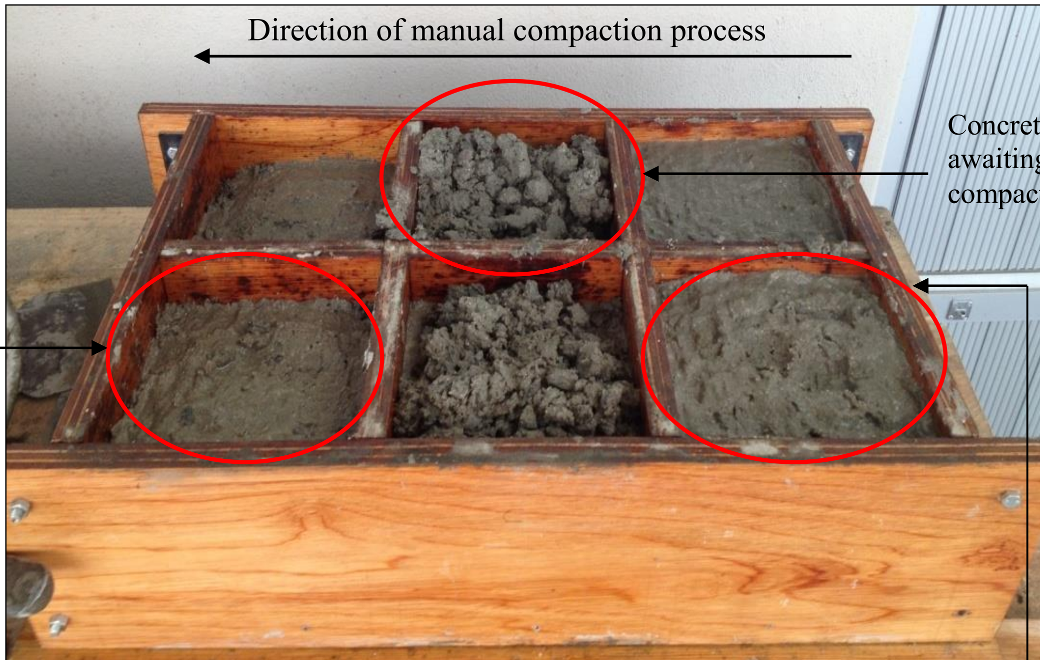


Figure 3.11: Manual compaction process of concrete overlay

Procedure:

1) Prepare the wooden moulds for casting. This includes placing a light coat of oil on the interior wooden surfaces as well as cleaning any leftover concrete from the previous mix.
2) Batch the ingredients for the overlay mix.
3) Ensure that the moisture conditions of the substrates are ready prior to casting of the overlays. In the case of the substrates which are in the saturated surface dry state, remove them from the curing tank 15 minutes before the overlays are going to be cast and place them on a table to rest. This will ensure that the excess water dissipates for a saturated surface dry state.
4) Dry mix the ingredients in the 15 l concrete mixer and slowly add the measured water to produce the overlay concrete repair mortar.
5) Place the substrates in the wooden moulds and assemble the boundary pieces for a tight fit. It is paramount that no oil flows onto the exposed substrate surface. This will weaken the bond strength and falsify results. See figure 3.9 and 3.10 for the assembly of the wooden moulds

6) Cast the overlay mix on top of the substrates in three different equal layers, with each layer receiving manual compaction. Complete the first layer of each of the six substrates before moving onto the second layer. This process is replicated until the 75mm overlay has been cast. Figure 3.11 provides a graphical representation of the compaction process.
7) Cover the wooden moulds with plastic and allow the concrete specimens to harden for 24 hours before de-moulding.
8) De-mould the repaired concrete members with great care, as the bond between substrate and overlay is still very weak.
9) Wrap the concrete specimens in plastic for curing and place them in the environmental room for 28 days.

Apparatus: a) 15l mixer, b) compactor and overlay mix storage bowl, c) wooden moulds

The following procedure was performed in the same manner for all three different substrates, and corresponding substrate moisture conditions. A total of 288 repaired concrete specimens were cast. This included different parameters such as substrate properties, moisture preparation and overlay properties. A detailed description of the different parameters being investigated can be found in section 3.8 (summary of variables). This section illustrates what the 288 concrete specimens were comprised of and how this final number of 288 concrete cubes came about.

Figure 3.12: Apparatus for the casting of concrete overlays

3.7 Curing of composite specimen

The final concrete composite specimen was cured for 28 days by covering all six sides with normal household plastic wrap (figure 3.13). Although this was a simple process, the curing was an important part of the experimental procedure in providing suitable bond strength. This ensured that the moisture both in the overlay and substrate was not lost to the environment, but rather encouraged further cement hydration both in the overlay and the bond interface. The specimens were left to cure in the environmental room for 28 days at a relative humidity and temperature of 50% and 22 ± 0.5°C respectively for consistency with the substrates, as well as allowing for maximum possible bond strength.

The curing tanks were not utilised for the repaired specimen simply because this would influence the moisture preparation of the substrate and go against what was set out to be achieved.

Figure 3.13: Repaired specimens covered in plastic for curing (28 days)

3.8 Summary of variables

The experimental procedure performed to investigate the influence of moisture preparation on overlay bond strength included a number of different parameters as mentioned in section 3.5 and 3.6. Below a detailed review of the different variables are described.

There were three different substrates which were cast in the laboratory, namely: S1, S2 and S3. These represented a concrete mix with a strength grade of 50, 30 and 20 MPa respectively. Each of the three substrates was sandblasted to roughen the surface and was exposed to four different moisture conditions prior to repair.

The concrete overlays comprised of four mixes, two different strength grades and two different workable mixes. The overlay mixes were represented by O1a, O2a, O1b and O2b. The number represented the strength of the mix and the letter the workability. Therefore the number of repaired specimens required for testing is illustrated below.

Repaired specimens = 3(substrates) x 4(moisture conditions) x 4(overlays) x 6(results)
= 288 repaired specimens

The '6 results' represented in the above equation was the number of repaired specimens per single parameter being investigated i.e. there were 6 different 150 mm cubes with the same substrate, moisture condition and overlay mix in order to create a more consistent result. Appendix A describes the order in which the casting of the concrete overlays was carried out, together with their bond strengths.

3.9 Experimental testing

There were many experimental tests which could have been utilised for the determining of bond strength between the existing substrate and concrete repair mix. These include the pull off test, biaxial bending test, double shear test etc. However many of these test procedures induce unwanted tensile and bending stresses, and are tricky to perform. Therefore the experimental method which was utilised was the interface shear bond test. This particular test is simple, practical for what was wanted to be achieved and produced a quick turnover time between specimens.

The interface shear bond test is characterised by applying a shear force directly at the substrate/overlay interface, without creating any eccentricities which may incur tensile stresses in the member. The procedure only requires a compression machine, a steel loading brace and a 150 mm concrete cube sample comprising of the substrate and overlay. Although the procedure was very simple, the results obtained were assumed to be an accurate reflection of bond strength (Momayez *et al*, 2004). The apparatus and testing procedure are discussed further.

Apparatus

- Amsler compression machine
- Steel loading brace
- Measuring ruler
- Lubricant (petroleum jelly) for stress transmitters

The most important apparatus of the interface shear bond test was the steel loading brace. This was responsible for not only keeping the repaired specimen in place for testing, but also channelled the compressive force from the compression machine directly through the interface of the specimen. This eliminated any eccentricities and hence tensile stresses which would negatively impact the results. Figure 3.14 illustrates how the compressive force was channelled from the steel loading brace into the repaired specimens interface.

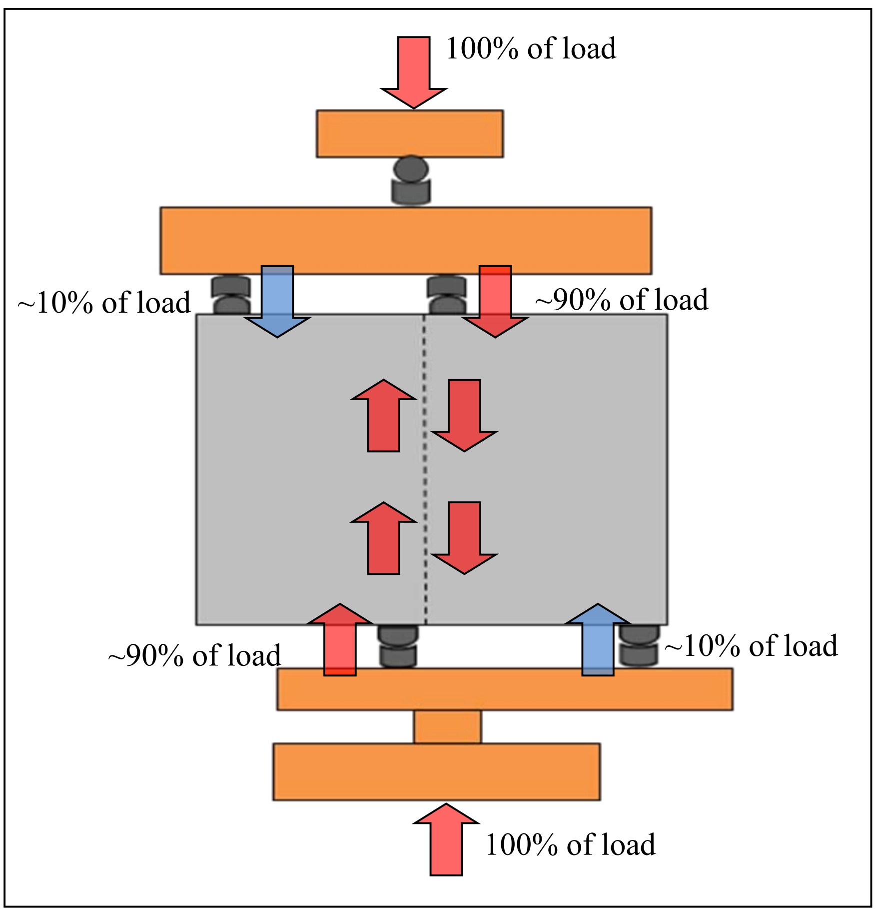


Figure 3.14: Distribution of forces on steel loading brace

Procedure:

1) Collect the composite specimens for testing, separating them according to substrate moisture preparation and overlay properties.
2) Prepare the steel loading brace i.e. clean and apply petroleum jelly to the loading pads.
3) Remove the repaired concrete specimen from the curing plastic and clean two of the best looking opposite interfacial sides.
4) Place the base of the steel loading brace in the compression machine, with the repaired specimen resting on top. Ensure that the two opposite interfacial sides which were cleaned are now situated on the top and bottom of the plate.
5) Place the top piece of the loading brace on to the concrete specimen, making sure that the loading pads are 2mm away from the interfacial zone (top and bottom pad)
6) Perform a final check to ensure that the loading brace and concrete specimen line up properly.
7) Slowly apply a compression force, with a loading rate of 1 kN/s. The slow loading rate applied was to ensure that there was no sudden stress spike at the interface which could falsify results. This also ensured consistency throughout concrete bond testing
8) Continually apply load until failure and record result, making observations on the different failure mechanisms.

The experimental testing for bond strength was performed when the concrete specimens reached the 28 day curing date. All tested specimens were labelled and stored in the labs for reference for further bond failure surface inspections.

3.10 Analysis of results

Once the results were obtained, the analysis could commence. The results were analysed in two different approaches. The first approach was along the lines of a more qualitative nature, whereas the second approach incorporated a statistical background to identify relationships which would have otherwise been lost within the data.

The next chapter discusses the results and analyses procedures followed in order to identify important relationships between the different factors measured while completing the concrete bonded overlay tests.

4. Results and Discussion of Results

4.1 Introduction

This chapter discusses the results obtained from the experimental procedures described in Chapter 3. The results discussed include the strength, workability and moisture preparation of overlay and substrate, as well as how they affect the bond strength of the repaired member. Since concrete repair is a complex problem and involves many independent variables such as the ones aforementioned, two different analyses were performed, namely: The descriptive analysis and the full factorial statistical analysis.

The two above mentioned analyses were included to provide: 1) Results which would isolate the different factors and determine how they singularly impact the bond strength and 2) Determine how the factors affecting bond strength collectively relate to one another. With respect to the full factorial analysis, the statistical software programme MATLAB was utilised to perform an ANOVA (Analysis of Variance) on the results.

The two analyses indicated that the bonded interface shear tests produced results where substrate moisture preparation of the repaired specimen displayed little influence on bond strength; However, where there was an increase is bond strength, the substrate was in a dry state. Furthermore, the failure location of the bonded concrete overlay generally occurred either 1-2mm within the substrate or overlay. This was dependent on the strength grade of both overlay and substrate. The moisture composition of the substrate and workability of the overlay also impacted the failure location and appearance and is discussed further in section 4.2.3.

4.2 Descriptive results

The results obtained in this particular section provide a medium in which relationships between variables and bond strength can be identified without any extensive statistical manipulation. Although this particular method of analysis was fairly easy to implement and yields appropriate results, one should not read too much into them before applying a full factorial statistical analysis.

The interface shear bond test provided instantaneous bond strength results when the repaired concrete specimens were tested. Once all the specimens were tested, outliers within the data were identified using boxplots and excluded. The presence of outliers within a data set can greatly distort statistical estimates and inflate error rates. A total of 8 outliers were detected and are presented in appendix B.

Once the outliers were eliminated from the data set, the mean bond strength was calculated in order to find any trends within the results. Table 4.1 illustrates the mean bond strength values for the different repaired specimens according to substrate and overlay composition and moisture preparation.

From the table it is clear that the highest average bond strength, represented by the highlighted blocks, between substrate and overlay was almost always obtained when the substrate was in a dry state; however the other factors which are involved in the bonding process (i.e. workability and strength) and how they interact are not accounted for. To try and get a sense of how these factors influenced the bonds strength together with the moisture preparation, a series of bar charts were developed.

Table 4.1: Comparison of bond strength results

Comparison of results	Average Bond Strength (MPa)			
Substrate 1	Moisture Preparation (M)			
Overlay Mix (O)	M1 - SSD24h	M2 - SSD30m	M3 - RT	M4 - OD24h
O1a	4.4	4.3	4.5	4.5
O1b	4.6	4.4	4.2	4.9
O2a	3.3	3.7	3.0	3.6
O2b	3.2	3.0	3.3	3.7

Comparison of results	Average Bond Strength (MPa)			
Substrate 2	Moisture Preparation (M)			
Overlay Mix (O)	M1 - SSD24h	M2 - SSD30m	M3 - RT	M4 - OD24h
O1a	3.8	3.5	4.8	4.1
O1b	4.1	4.7	5.0	4.8
O2a	3.2	3.4	3.5	3.5
O2b	3.5	3.4	3.6	3.5

Comparison of results	Average Bond Strength (MPa)			
Substrate 3	Moisture Preparation (M)			
Overlay Mix (O)	M1 - SSD24h	M2 - SSD30m	M3 - RT	M4 - OD24h
O1a	3.9	3.4	4.0	3.9
O1b	3.2	3.6	3.9	4.0
O2a	2.6	3.3	3.2	3.0
O2b	3.2	3.4	3.7	3.6

4.2.1 Analysis of descriptive results

A series of bar charts were developed and categorised into two different groups, with each group being split into the three different substrates. These two groups differed according to the strength and workability parameter of the overlay. Group 1 varied the strength of the overlay and maintained constant workability, whereas group 2 varied the workability of the overlay and maintained constant strength. This allowed for the results to be analysed from two different perspectives in order to grasp a better understanding of how the bond strength was influenced. It should be noted that the standard deviation was included in the bar charts to show the variance within the data.

To further analyse data which the bar charts represented with respect to bond strength and the different tested parameters, a statistical comparison test was performed. The test was necessary to check whether the results between different moisture conditions were significantly different from one another. The statistical test which was implemented is known as the two tailed t-test statistic and was utilised with a 5% confidence level. Figure 4.1 illustrates the regions in which the null hypothesis (there is no significant difference between the bond strength means of the different tested substrate moisture conditions) is rejected and therefore indicates that the recommended substrate moisture condition has the undesirable effect of reducing bond strength.

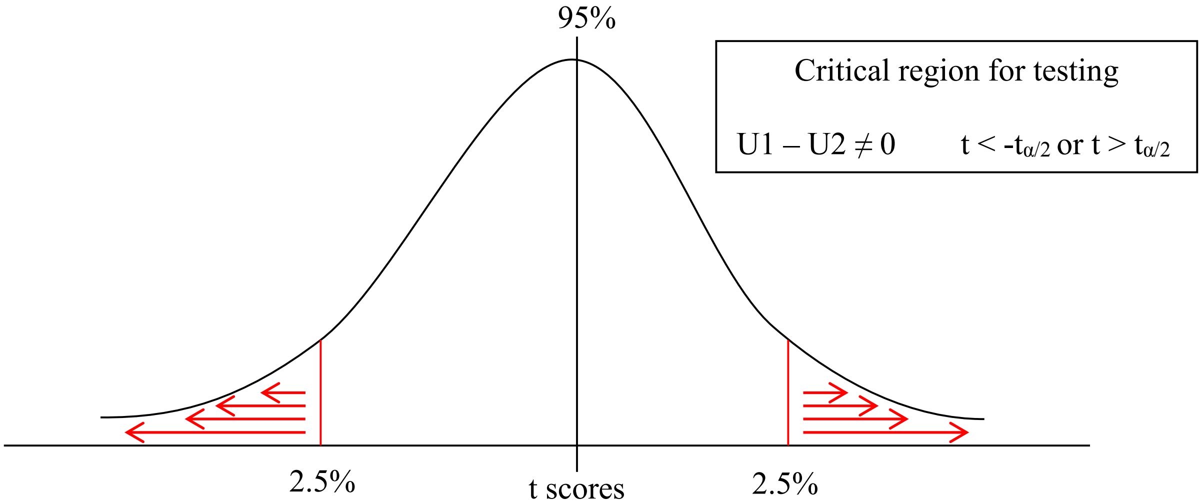


Figure 4.1: two tailed t-test statistic with 5% confidence level

The two tailed t-test can only be utilised for the comparison of two different means and therefore a number of tests were performed within each separate bar chart to fully analyse the effects of the four different moisture conditions. An example is illustrated below.

U1 & U2, U1 & U3, U1 & U4, U2 & U3, U2 & U4, U3 & U4

Therefore, six separate t-tests were performed for each bar chart. The results of the statistical test and bar charts follow.

Constant workability

Figures 4.2 – 4.4 illustrate how the moisture preparation affected the bond strength of the repaired specimen, with the strength of the overlay varied and the workability kept constant. It can be seen that there was a general increase in the bond strength, as the strength of the overlay increased from 25 MPa to 40 MPa. This was evident for all three tested substrates, regardless of substrate strength; however the degree of strength gain achieved by the overlay mixes was governed by how strong the subsequent substrate concrete was. For instance, the stronger substrate (S1 – 50 MPa) showed an average percentage increase of 35% when the overlay strength increased, whereas the weaker substrates (S2 – 30 MPa and S3 – 20 MPa) displayed an average percentage increase of 27% and 16% respectively. These percentages included both overlay workability conditions i.e. 30 mm and 120 mm concrete slump. The reasoning behind this phenomenon can be attributed to the failure mechanism which the repaired specimen experienced. When the substrate is weak, the added strength of the overlay will not play a considerable role in increasing the bond strength. Bond failure often occurred close to the interface in the substrate concrete. The same was true for a repaired specimen with a strong substrate and weak overlay. Further analysis on the failure mechanisms are provided in section 4.2.3

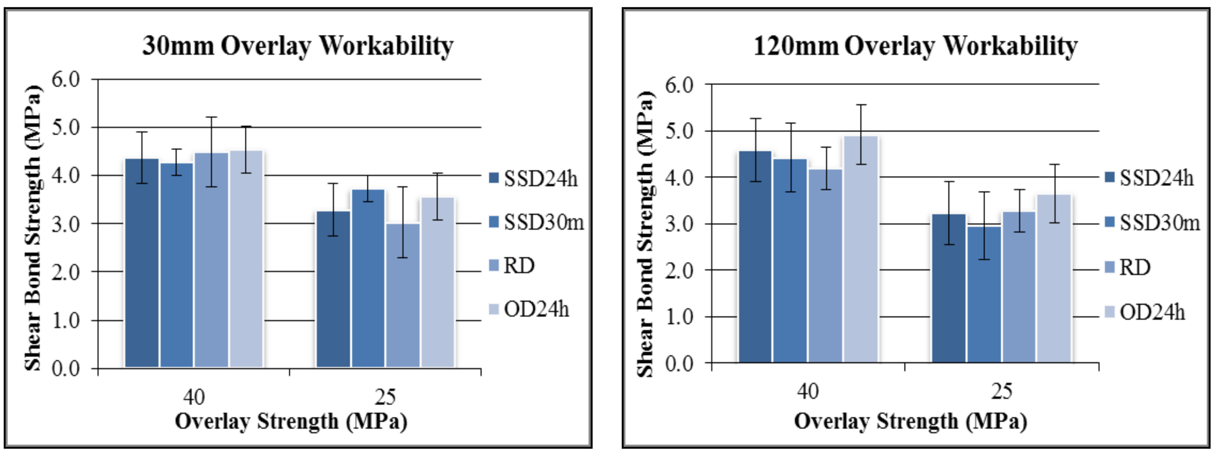


Figure 4.2: Comparing overlay strength with constant workability (Substrate 1)

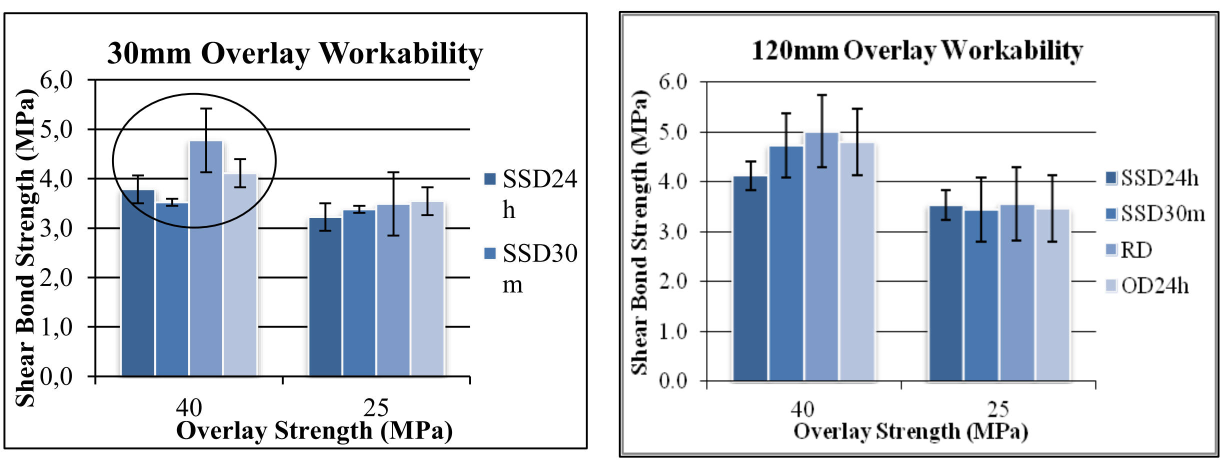
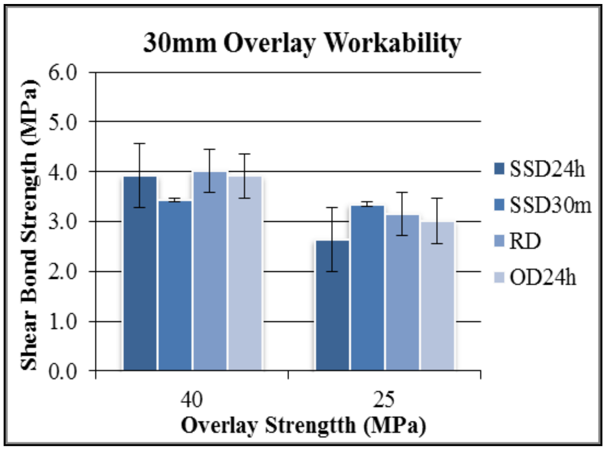


Figure 4.3: Comparing overlay strength with constant workability (Substrate 2)



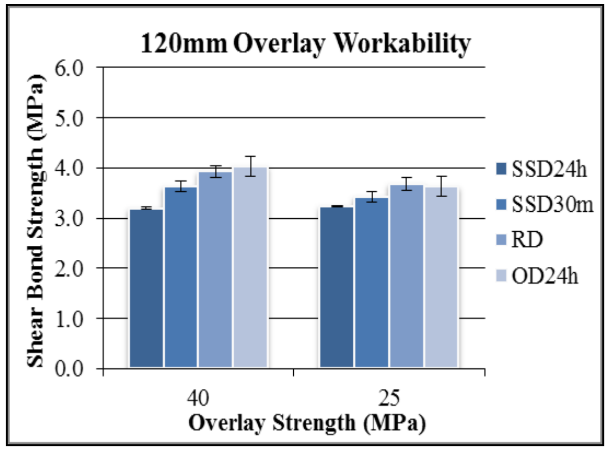


Figure 4.4: Comparing overlay strength with constant workability (Substrate 3)

Figures 4.2 – 4.4 also indicate a trend when comparing the different bond strengths according to substrate moisture preparation. From the results, pre-wetting the substrate provided no increase in bond strength regardless of the strength of the overlay. In many instances, pre-wetting the substrate resulted in a reduction in bond strength in comparison to either subjecting the substrate to ambient room temperatures or oven drying at 50°C for 24 hours. However, although there was a general upward trend in bond strength as the substrate shifted to a dry state, the results were not statistically significant from one another. This was the case for all bar charts barring one. The circled bar chart in Figure 4.3 illustrates a substantial decrease in bond strength when subjected to substrate pre-wetting while comprising of a strong, stiff overlay. The results rejected the hypothesis from the two tailed t-test and thus indicated that pre-wetting the substrate under those conditions actually decreases bond strength. Further interpretation of the influence of substrate moisture preparation is provided in section 4.2.2.

Constant overlay strength

Figures 4.5 – 4.7 illustrate how varying the workability of the overlay, together with applying different moisture conditions to the substrate affects the bond strength with overlay strength kept constant. In these figures it was surprising to see that the increase in overlay workability did not have a great deal of influence on the bond strength of the repaired specimen. The idea was that a more workable mix would have been able to flow easily into the capillary pores of the substrate and thus encourage better mechanical interlock. However this was not the case, as the stiff 30 mm concrete overlay produced similar bond strength results irrespective of overlay and substrate strength.

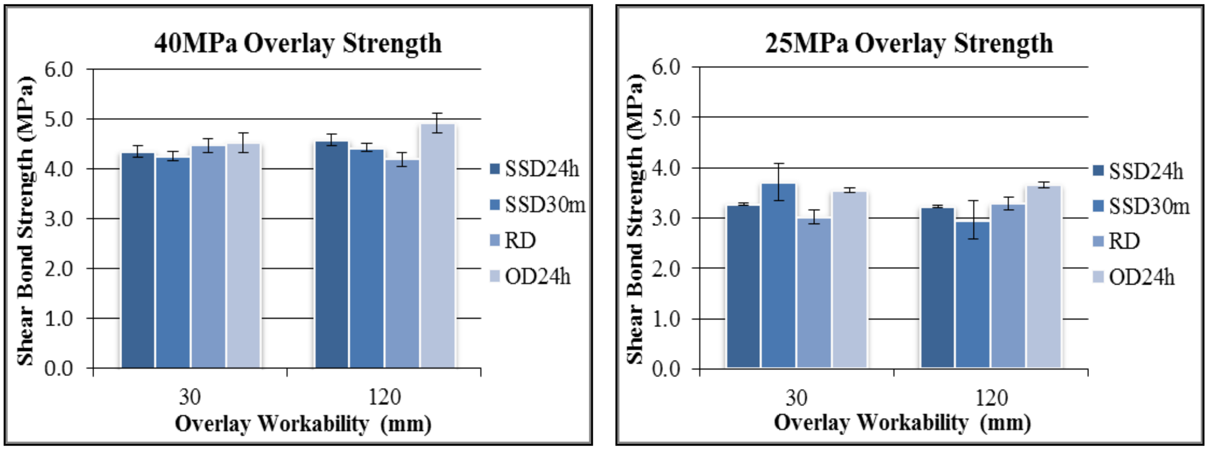


Figure 4.5: Comparing workability with constant overlay strength (substrate 1)

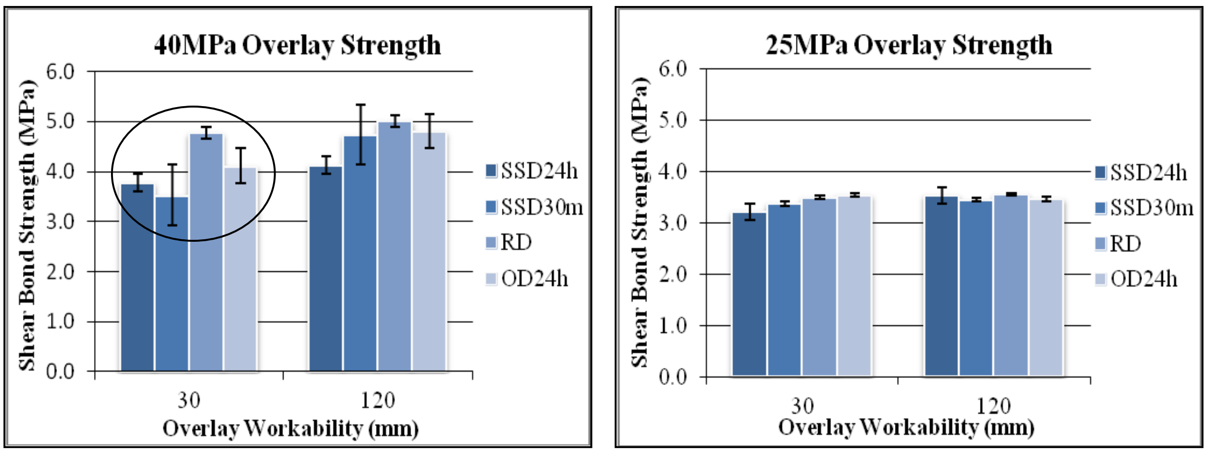


Figure 4.6: Comparing workability with constant overlay strength (substrate 2)

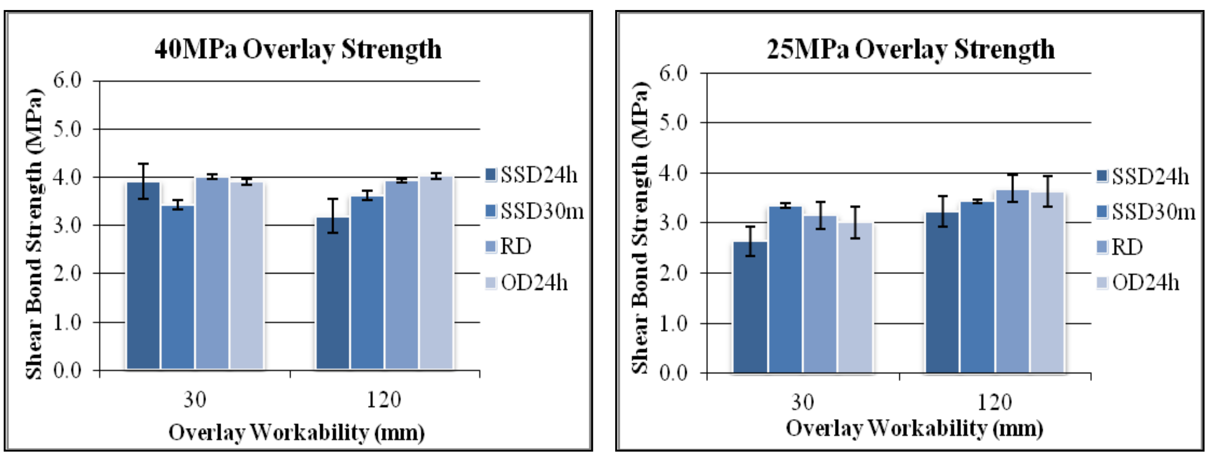


Figure 4.7: Comparing workability with constant overlay strength (substrate 3)

One of the possible reasons for these results may have been due to the compaction process when casting the overlays. As mentioned in the previous chapter, the concrete overlay was compacted in a thorough and meticulous manner. This ensured that the concrete, irrespective of the workability, was able to flow readily and construct a consistent mechanical interlock with the substrate. As a result, the workability of the overlay for a given strength grade, induced very little influence on the bond strength. One could therefore argue that the workability of the overlay is not particularly important with respect to bond strength, provided that the compaction process is carried out in a professional manner as performed in section 3.6.3. Figure 4.8 displays how the workability of the overlay together with proper compaction can result in better mechanical interlock between substrate and overlay.

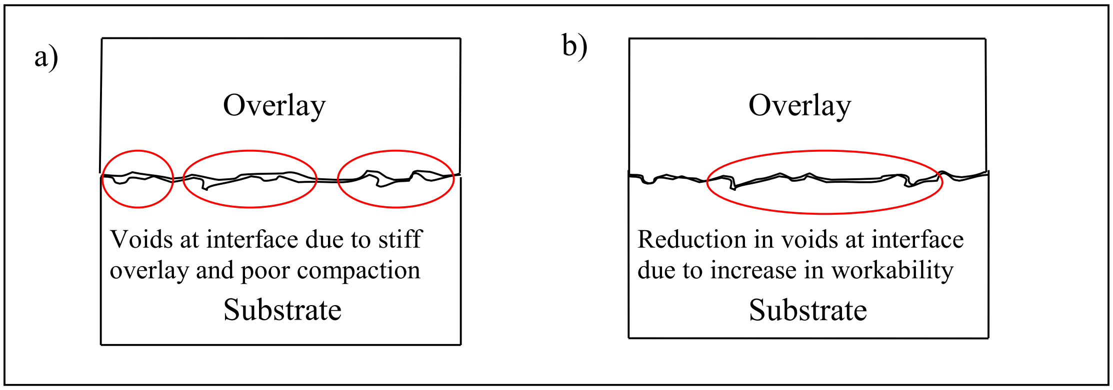


Figure 4.8: Comparison between a stiff (a) and workable (b) overlay mix

Figure 4.8a) represents the repaired specimen without proper compaction, and to a certain extent, an overlay mix which was very stiff. There were many voids between the substrate and overlay which reduced the mechanical interlock and hence the bond strength. On the other hand, Figure 4.8b) represents a repaired specimen where proper compaction of the overlay mix was performed. Here the interface zone between substrate and overlay contains very few voids and combines in a uniform manner creating a strong bond. It should be pointed out that even if a workable overlay mix was utilised; if the proper compaction process was not performed, then the same situation in figure 4.8a) would occur.

A further observation made in figures 4.2 – 4.7 was the influence of substrate strength on bond strength of the repaired specimen. It was clear that when the overlay mix was of a lower strength (i.e. 25 MPa) the bond strength remained fairly consistent across all different substrates. The reasoning behind this phenomenon can again be explained by investigating the failure mechanism of the member. In all of the previous mentioned cases, the repaired specimen failed close to the interface, but in the weak overlay concrete. Therefore, the added strength of the substrate was not able to provide any benefit towards bond strength. This promotes the fundamental principle in concrete repair that the applied overlay should always be of a similar or greater strength than the substrate. From the aforementioned it can be seen how concrete repair requires the integration of materials and that there are many different factors which can influence the bond strength of a repaired concrete specimen. Not only do these factors influence the bond strength on an individual capacity, but collectively as well. The influence of moisture preparation and experienced failure mechanisms are discussed in more detail below.

4.2.2 Influence of moisture preparation

The influence of moisture preparation on the bond strength of the repaired specimens was far from substantial. However, in many instances, the results from pre-wetting the substrate as shown in figures 4.2 – 4.7 indicated a clear positive trend when the substrate of the repaired specimen moved to a drier state. Therefore one can conclude that substrate pre-wetting provides no positive influence on bond strength. To further challenge the views of current practice with respect to moisture preparation and the results obtained in this investigation, a statistical analysis was included to see whether pre-wetting the substrate not only provides no increase in bond, but negatively influences bond strength.

The two tailed t-test was included for this analysis and is described in section 4.2.1 together with the allocated parameters and hypothesis. The results from the statistical analysis showed that out of the 24 different variations of the bar charts, two provided results which were statistically significant in rejecting the null hypothesis and thus concluding that substrate moisture preparation negatively affected bond strength in these situations. The two significant results were both obtained with substrate 2 (30MPa) and an overlay strength of 40 MPa and workability of 30 mm. The scenario in which the null hypothesis was rejected is circled for easier reference.

Although there is no clear tested reason why the added moisture results in lower bond strength values and in some cases negatively affected bond strength as described above, certain assumptions can be attained from the literature. It was previously discussed in chapter 2 that in order to achieve a reasonable bond or strong mechanical interlock between substrate and overlay, the overlay must interact with the pore structure of the substrate, i.e. the overlay fills the unsaturated cavities and pores of the substrate and creates a uniform member. Therefore, the potential problem which may arise when pre-wetting the substrate surface is that the added water may fill all the empty cavities within the concrete and as a result create a buffer which prevents the overlay from fully interacting with the substrate. This particular viewpoint was witnessed when the failure surfaces of the concrete bonded overlays was smooth and represented almost no interlock between the new and old concrete. Section 4.2.3 justifies the above mentioned statement with reference to tested concrete bonded overlays.

On further analysis of figures 4.2 – 4.7, it was interesting to note that the bond strength of substrate 1(S1) was not affected by moisture preparation in the same way as S2 and S3. One proposed reason for the above result was due to the substrate properties of S1. S1 was characterised to be fairly impervious in section 3.5.2 with a very low porosity and absorption rate. Therefore, one could argue that these substrate properties nullified the moisture preparation effects as even when the substrate was not exposed to pre-wetting, the bond strength remained fairly constant throughout the different overlay repair mortars utilised. The only time where S1 experienced an increase in bond was when the substrate was oven dried. This would have cleared any moisture which filled the minimal pores present and thus allowed for a better mechanical interlock.

It was therefore clear that substrate moisture preparation (i.e. pre-wetting the substrate surface) had no positive influence on the bond strength of the repaired member, irrespective of substrate composition, and in some cases negatively affected bond strength. Thus, in order to maximise the bond strength on a consistent basis, it must be ensured that the substrates are in a dry state before the casting of overlays and that the overlay mix is relatively workable.

4.2.3 Location of bond failure

The failure location in a bonded concrete overlay can often exhibit important information about the characteristics of both the substrate and overlay, as well as how they interact with each other. Often in the strength tests which are utilised to determine bond strength, the location of failure is found on the weakest link in the composite member. Previous studies have developed the term 'overlay interface zone' and refer to the concrete which is found close to the interface of the existing substrate. This particular concrete has similar characteristics to the concrete which is found between the aggregate and cement paste, i.e. the interface transition zone, and both relate in that they are weak compared to the existing cement paste around them (Beushausen & Alexander, 2008). The possible reason for the creation of this weak interface zone within the overlay can be attributed to the absorption properties of the substrate as well as substrate preparation. Therefore the location of the bond failure was considered of importance to this particular investigation in order to determine how moisture preparation, as well as concrete properties (workability, strength) influences the bond mechanics.

Bond failure of substrate 1

The specimens which comprised of substrate 1 (50 MPa) generally displayed overlay failure with a very thin layer of the overlay (<2 mm) still adhering to the substrate surface. This was the case across all four different moisture conditions, however the manner in which the overlay adhered to the substrate varied according to the moisture and overlay properties. When the overlay mix comprised of the strong concrete (40 MPa – irrespective of workability) tiny pieces of the substrate would chip off the edges and adhere to the overlay upon failure, thus providing visual evidence of strong mechanical interlock. This observation was only true when the substrate was in a dry state, i.e. no substrate pre-wetting took place. Furthermore the surface texture of the failure location when the substrate was in a dry state with the strong overlay mix was very rough. The opposite was observed when the substrate was exposed to pre-wetting. Here the failure surface texture was smooth with no traces of substrate concrete adhering to the overlay. These observations provide insight into the interactions between the different properties of existing and new concrete, and are presented in figure 4.9. Figure 4.9 illustrates how the bond failure changed as the substrate moisture condition varied for O1b and subsequently resulted in an increase in bond strength. Note that the substrate is on the left and the overlay on the right. The white pieces on the repaired specimen were where the substrate failed or was pulled off by the overlay.

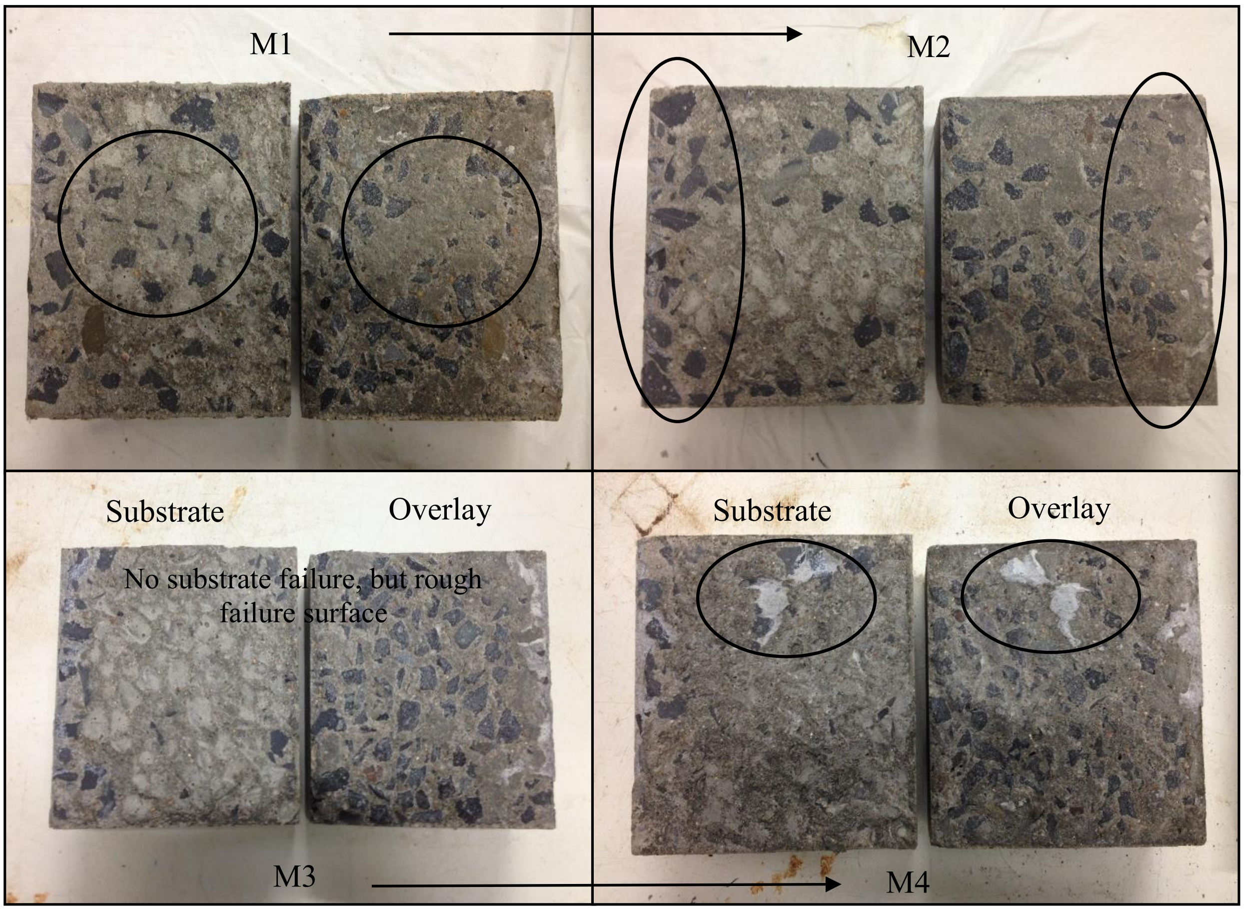


Figure 4.9: Bond failure of O1b on Substrate 1

The weaker overlays (O2a and O2b) experienced very similar failure mechanisms not only across all moisture conditions which they were exposed to, but also with respect to the stronger overlays. Here however, there were no signs of small pieces of substrate being pulled off. One interesting observation which was made with respect to the weaker overlays was that as the overlay increased in workability, the surface roughness of the bond failure became smoother when the substrate was exposed to pre-wetting. The added moisture decreased the potential mechanical interlock experienced between substrate and overlay and as a result, negatively affected the bond strength at that particular moisture condition. Figure 4.10 illustrates the comparison bond failure location and appearance between the above mentioned O2a and O2b when the substrate was subjected to pre-wetting, where figure 4.11 illustrates the subsequent change in bond strength.

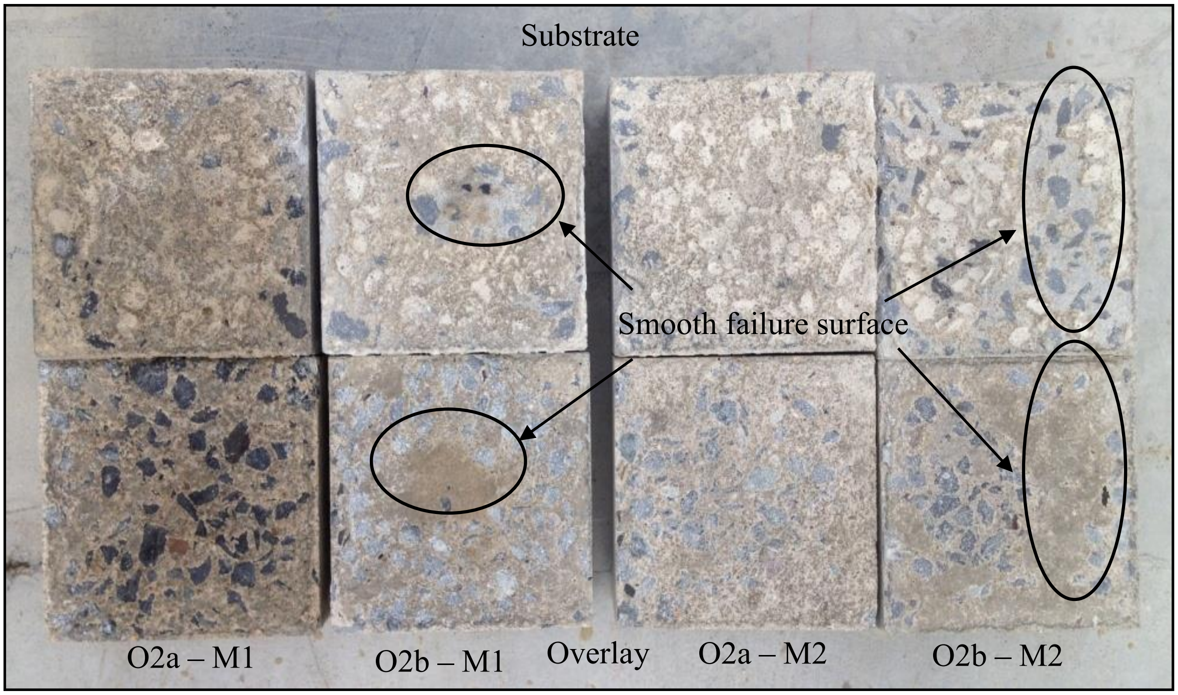


Figure 4.10: Bond failure of O2a and O2b with substrate 1 (pre-wetting)

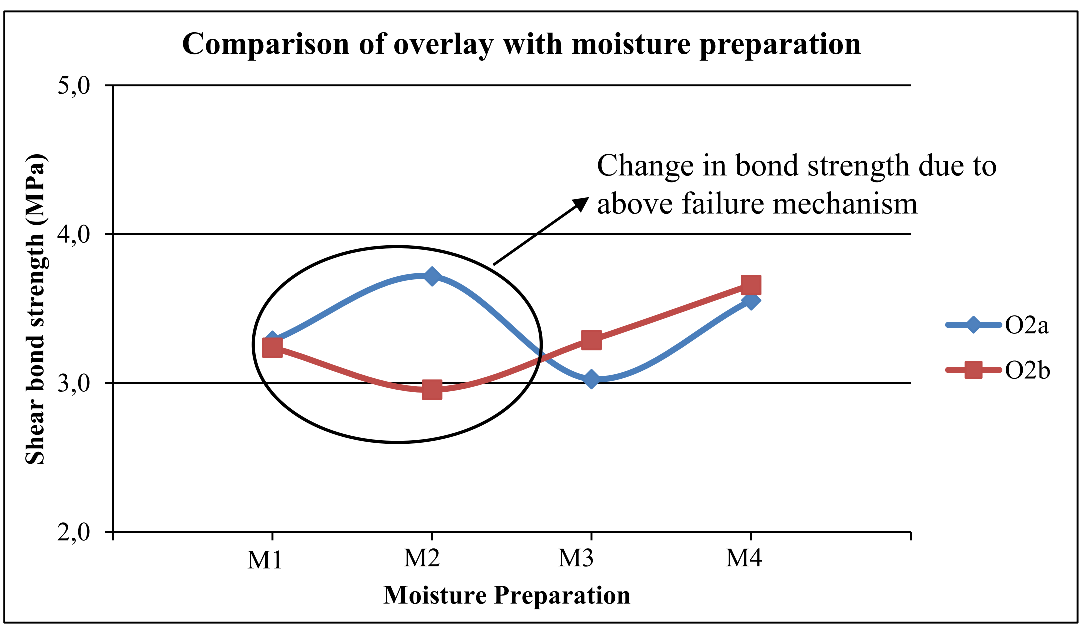


Figure 4.11: Change in bond strength between O2a and 02b from failure mechanism

Therefore when comparing the different failure locations corresponding to the overlay mixes and substrate moisture conditions of substrate 1, it was noted that the moisture condition does slightly influence the appearance of the failure mechanism and to a certain extent the bond strength, although the bond failure location remains constant (overlay interface). The small pieces of substrate adhering to the overlay were another indication of the improved mechanical interlock between substrate and overlay when the moisture condition shifted to a dry state.

Bond failure of substrate 2

The concrete specimens made with substrate 2 (30 MPa) again represented failure mechanisms which were consistent with respect to the different moisture conditions utilised. However, because the overlay concrete (O1a and O1b) was now stronger than the substrate concrete, substrate failure was experienced. One of the suggested causes for the lack of influence of the SSD moisture condition for substrate 2 was due to the permeability and sorptivity characteristics of the substrate as mentioned in table 3.1. Now that the substrates absorption capabilities have been enhanced from S1, a dry substrate has the ability to interact more with the overlay mix.

The location and surface texture of the failure mechanisms for the stronger 40 MPa overlay mix only differed when changing the workability. The stiff 30 mm mix displayed shallow, smooth bond failure primarily in the overlay, whereas the workable 120 mm mix displayed a rougher and deeper bond, and failed in both overlay and substrate for all moisture conditions. If one had to analyse the bond strength results for just these two mixes for substrate 2, an interesting result follows in that an increase in overlay workability results in an increase in bond strength. Therefore the above mentioned bond failure location and appearance does provide evidence of how certain concrete parameters affect bond strength and is of great importance when analysing bonded concrete overlays. Figure 4.12 illustrates the aforementioned increase in bond strength when comparing the two different mixes. However this was only the case for the strong overlay mix which was bonded to substrate 2. The above observation again illustrates how dependant the bond strength is on other factors such as substrate characteristics, overlay strength and workability and moisture conditions of the substrate.

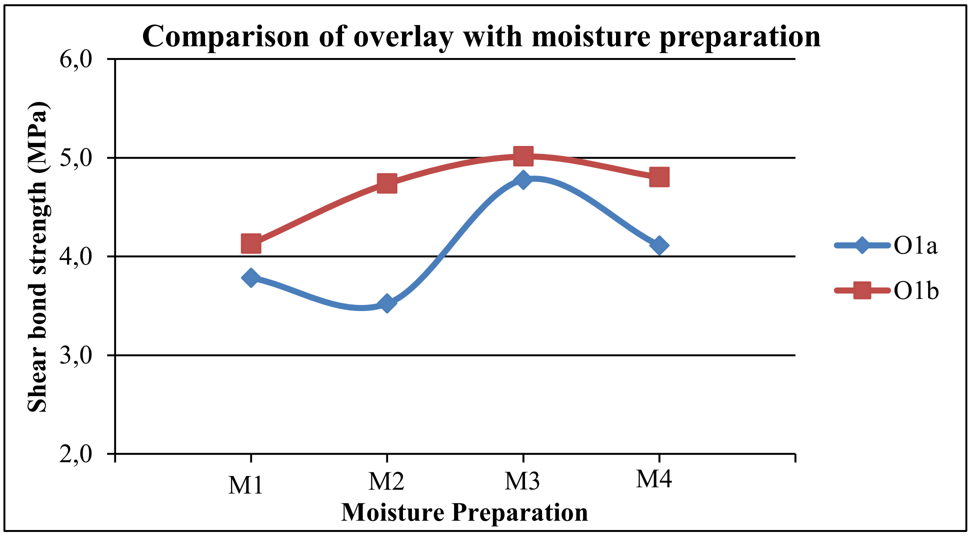


Figure 4.12: Comparison of bond strength between overlay 1a and 1b

Conversely, the different workability utilised in the weaker overlay mix (25 MPa) for substrate 2, yielded no profound changes in bond strength results together with the different substrate moisture conditions. The only noticeable observation was the increase in bond failure surface roughness and the presence of small substrate pieces attached to the overlay upon failure when the moisture condition of the substrate was in the dry state. However, this observed increase in mechanical interlock only slightly increased the bond strength. The weaker 25 MPa mix was not strong enough to reach its potential bond strength with the substrate and always prematurely failed in the overlay before any notable differences in bond strength correlated with bond failure location observations.

Bond Failure of substrate 3

The bond failure locations for the repaired specimens comprising of substrate 3 (20 MPa) almost always failed in the substrate for the strong overlay mixes, regardless of workability, and failed in the overlay for the weaker overlay mixes. As observed previously, the change in moisture conditions of the substrate, together with the change in the workability of the overlay mix, provides a visual indication when analysing the bond failure locations of why the bond strength either increases or decreases.

When analysing the overlay mixes O1a and O1b, an interesting observation was noted. In all cases the repaired specimen failed in the substrate, with a thin layer of substrate (1-2 mm) adhering to the overlay surface. This was consistent with all four different moisture conditions; however the thickness of the adhering substrate generally increased as the substrate moisture condition changed from wet to dry, together with an increase in overlay workability. The above observations did not amount to a substantial increase in bond strength, as the substrate strength was the limiting factor in this situation and hence did not allow the concrete specimen to achieve maximum bond before failure. The observed bond failure location can again be a cause of the substrate properties and how they interact with both the overlay mix and applied substrate moisture condition. Substrate 3 represented a poor grade of concrete and as a result it was characterised with a very high absorption and porosity rate, as noted in section 3.5.2. These values suggested that the substrate concrete contained many cavities within the pore structure which the overlay could interact with. However, when the substrate was pre-wetted to a SSD state, the cavities within the concrete were filled with water and prevented the overlay from forming a strong mechanical interlock. It is suggested that this is why, when the substrate shifted to the dry state, the amount of substrate which was pulled off the specimen upon failure increased. Figure 4.13 illustrates the fundamentals of the argument.

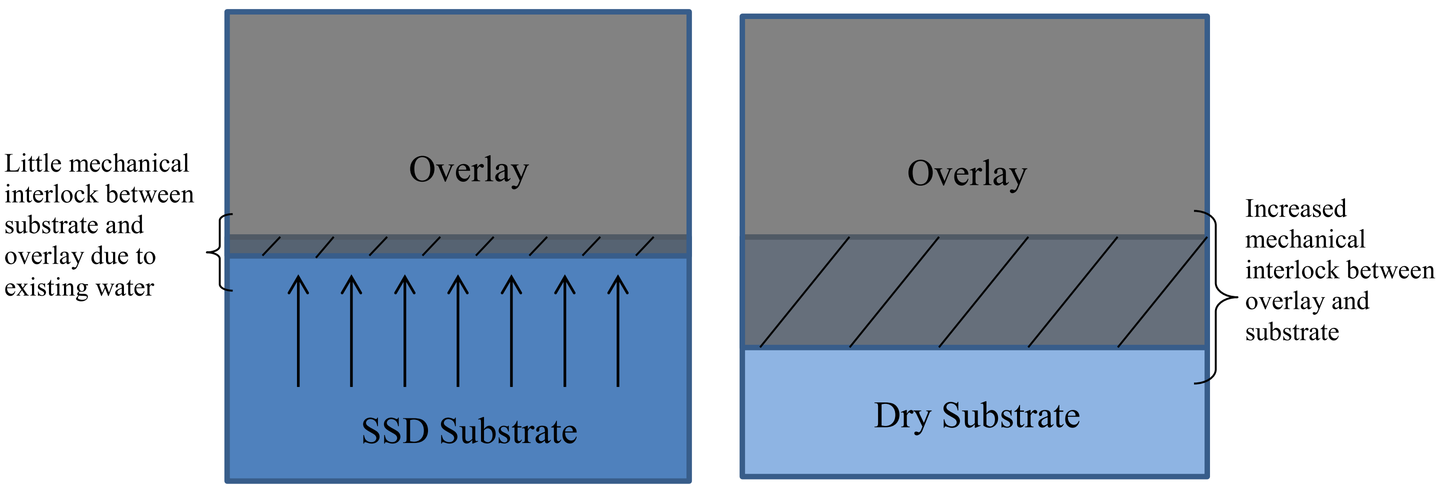


Figure 4.13: Mechanical interlock between substrate and overlay (varying moisture)

Figure 4.13 illustrates the above mentioned theory by depicting an increase in the substrate adhering to the overlay as the moisture condition shifted to a semi-wet/dry state, while utilising a stiff overlay mix (O1a). The result is however far more conclusive when analysing the interaction between the more workable 120 mm overlay mix and the substrate. The reason for this is that the stiff overlay mix was more accommodating towards the pore structure of the substrate when in a saturated state, and did not possess the workability to take advantage of the open pore structure of the substrate when in a dry state. This allowed for a suitable bond as shown in the M2 case in figure 4.14 The maximum bond strength which was achieved in this instance was in fact when the moisture condition was in a dry state (M3).

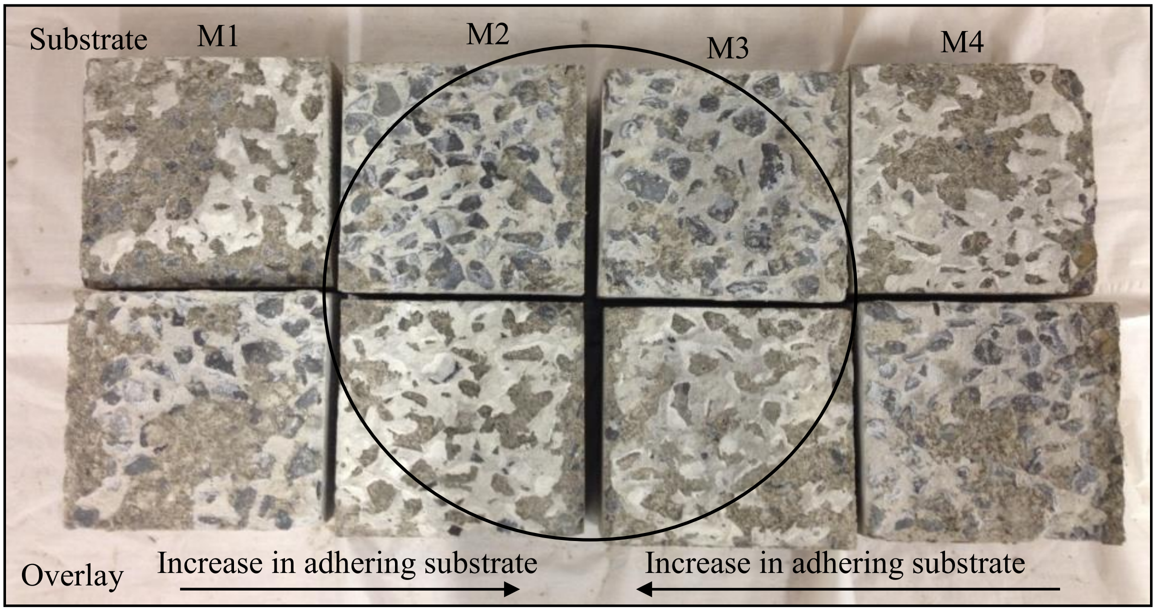


Figure 4.14: Comparison of failure mechanisms with overlay 1a

The failure mechanisms illustrated in figure 4.15 represent the interaction of the strong workable overlay mix (O1b) with the substrate comprising of different moisture conditions. The surface location of the bond failure within the substrate was enhanced and displayed strong mechanical interlock as the moisture preparation shifted to a dry state. Furthermore, figure 4.16 displays the subsequent increase in bond strength due to this observation. This again provides evidence which supports the theory represented in figure 4.13, in that failure surface locations are enhanced when the substrate was in a dry state.

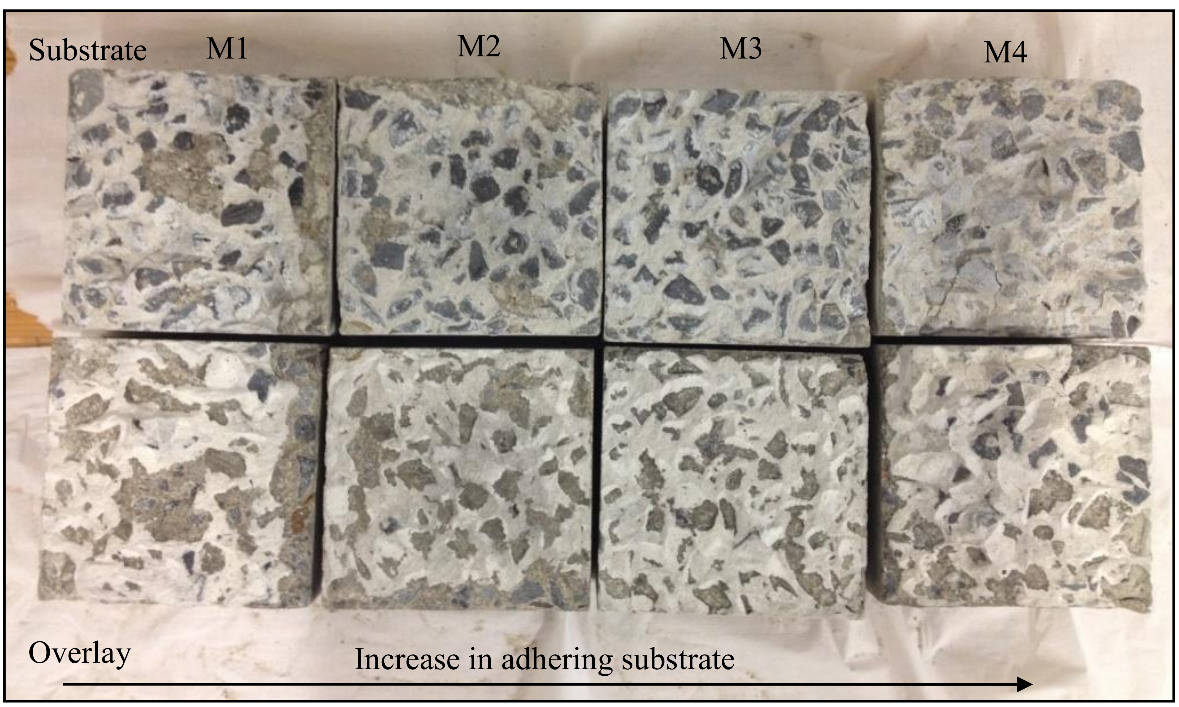


Figure 4.15: Comparison of failure mechanisms with overlay 1b

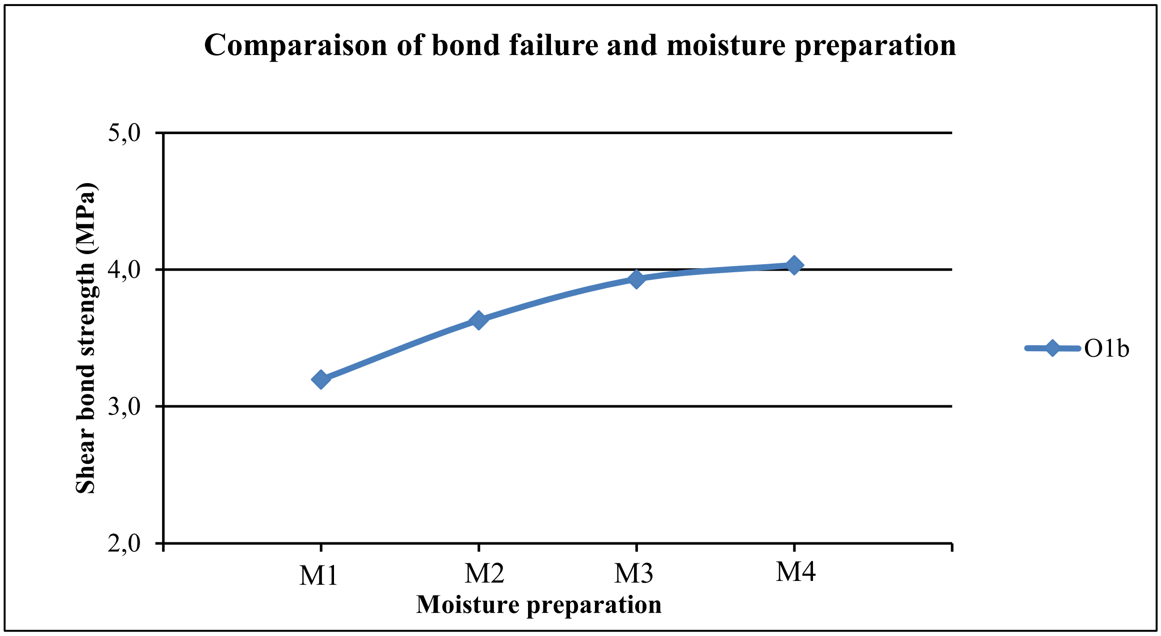


Figure 4.16: Bond failure and moisture preparation of O1b for substrate 3

The two weaker overlay mixes which were applied to substrate 3 displayed interesting bond failure locations. The stiffer of the two overlay mixes generally failed both in the overlay and substrate, with substrate failure around the edges and overlay failure in the centre of the repaired specimen. The surface roughness of the bonded overlay upon failure was also very smooth. However, the stiff overlay mix provided a greater bond in terms of pulling off the substrate when the substrate was in a SSD state. This observation can again be attributed to the substrate properties. Due to the fact that substrate 3 was designed to be a poor grade concrete, there were many cavities within the pore strucutre. Therefore, when the substrate was in a dry state, the open cavities drew moisture out of the overlay and left a harsh mix which was unable to create deep bond between the two layers. The opposite was experienced when the substrate was in the SSD state and is shown in figure 4.17. This observation did lead to a slight increase in bond strength and is shown in table 4.1.

When the overlay mix was adjusted to a more workable mix (120 mm – O2b) the bond failure location and appearance changed. Substrate failure was more prevalent and deep and shifted to a 50/50 overlay/substrate failure mechanism. The locations where the overlay failed were again generally in the centre of the specimen, now with a rough failure surface. When the workable overlay mix was applied to the substrate with dry moisture conditions, the bond failure occurred entirely in the substrate. This resulted in a small increase in bond strength. Figure 4.17 and 4.18 illustrates the comparison between the bond failure locations of O2a and O2b with substrate 3.

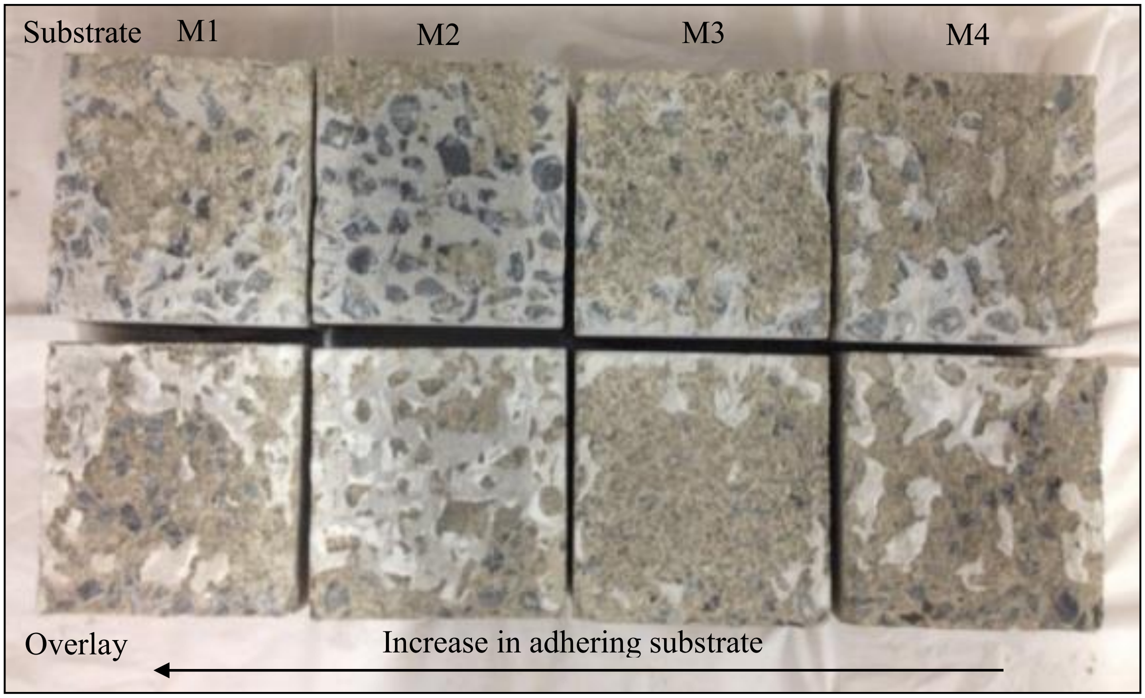


Figure 4.17: Comparison of failure mechanisms for O2a

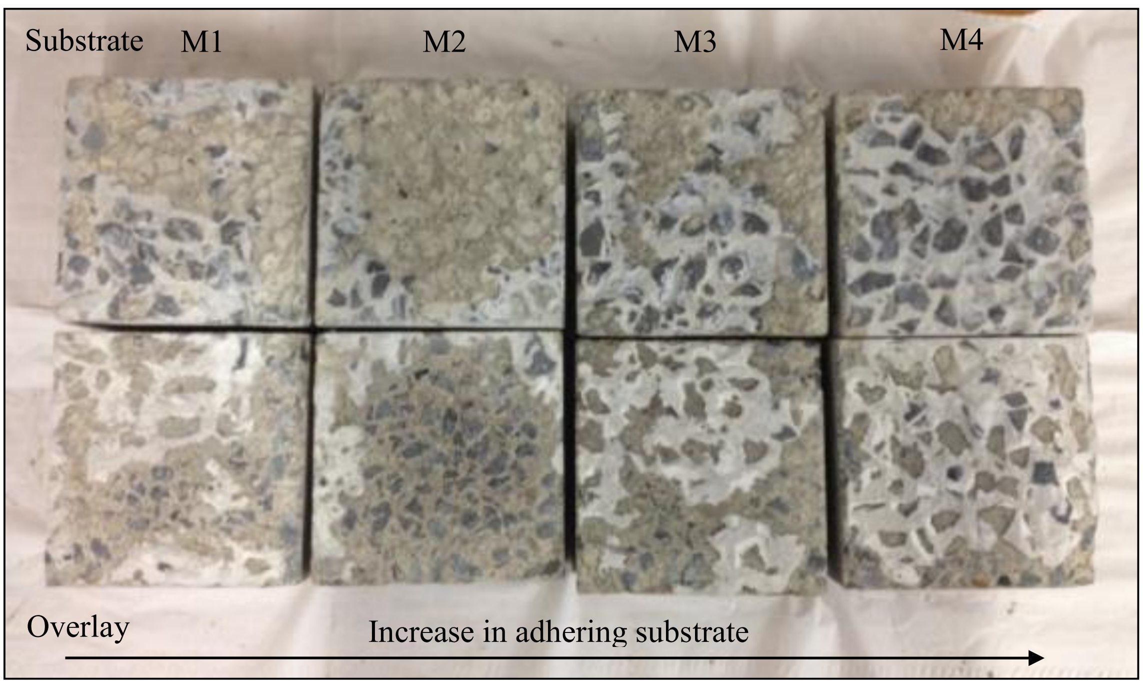


Figure 4.18: Comparison of failure mechanisms for O2b

4.3 Summary of bond failure locations

In general, the bond failure locations which were analysed across all three substrates, indicated better mechanical interlock between the substrate and overlay whilst in a dry state. However; this did not always lead to a higher bond strength value. To provide a brief summary of how the different tested repaired specimens failed, figures 4.19 and 4.20 provide graphical presentations of the four different failure modes which were experienced, whereas table 4.2 shows which of the four different failure modes were represented in each of the interface shear tests. The transition zone illustrated in figures 4.19 and 4.20 represents the interface between the overlay and substrate. This zone is not particularly thick (<1 mm) and failure in this zone was observed when little mechanical interlock was experienced. The failure surface was often very smooth.

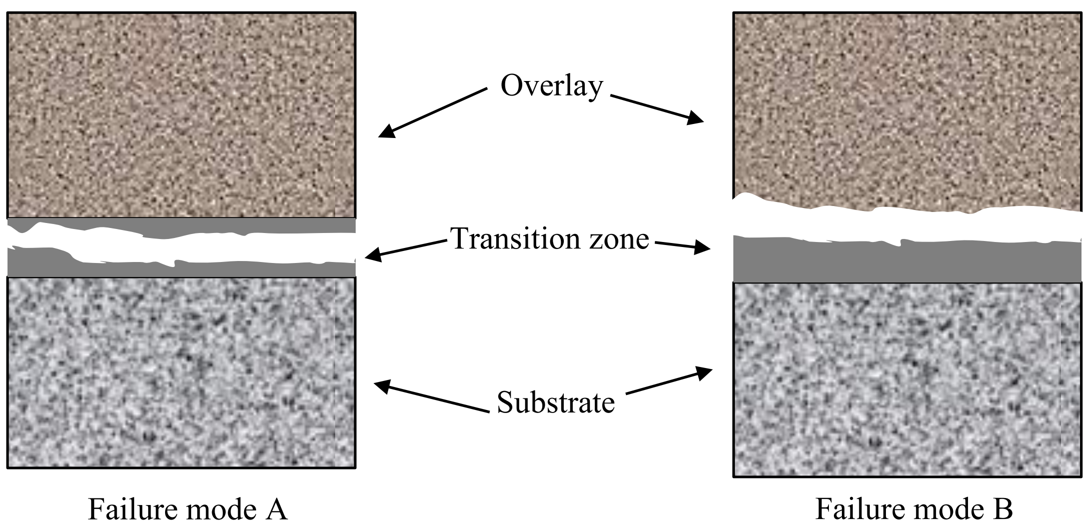


Figure 4.19: Failure modes A and B

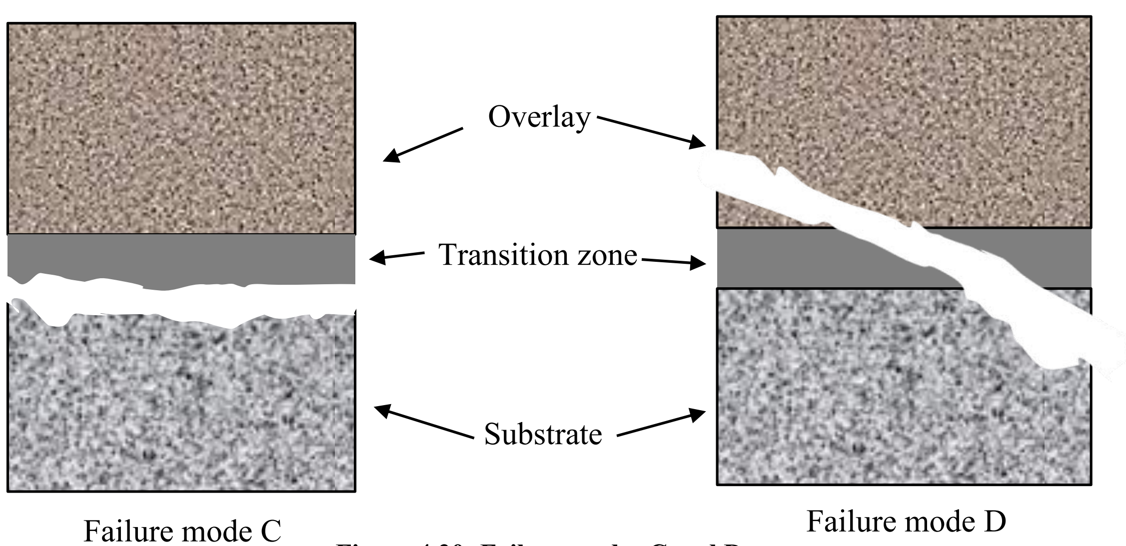


Figure 4.20: Failure modes C and D

Figure 4.19 represents bond failure in the transition of the repaired specimen i.e. at the interface between substrate and overlay (failure mode A), as well as bond failure within both the interface and applied overlay (failure mode B). Whereas figure 4.20 represents bond failure within the interface and substrate concrete (failure mode C) and bond failure in all three regions (failure mode D).

Table 4.2: Failure modes of repaired specimens

Moisture Prep (M)	Overlay (O)	Substrate 1	Substrate 2	Substrate 3
M1 - SSD (wet for 24 hours)	O1a	B	D	C
	O1b	B	D	C
	O2a	A	A&B	C
	O2b	B	B	D
M2 - SSD (Wet for 30 mins)	O1a	A	A & C	C
	O1b	B	A & C	C
	O2a	A & B	A&B	C
	O2b	A	B	D
M3 - Dry in ambient room temp (creep room)	O1a	B	A & C	C
	O1b	B	C	C
	O2a	B	A	C
	O2b	B	B & D	C
M4 - Oven dried for 24 hours at 50°C	O1a	A	C	C
	O1b	B	C	C (deep)
	O2a	A	A & C	C
	O2b	B	B & D	C

4.4 Conclusions of bond failure locations

From the above observations, it is evident how important it is to analyse the bond failure locations of the repaired specimen to achieve a better understanding of the mechanics behind the bond strength and how the different variables affect the bonding process. Below is a summary of the observations made:

- The substrate properties of the repaired specimen do play an important role in determining which overlay mix should be utilised together with which moisture condition. If the two are not compatible, the bond strength will be compromised as in the case for substrate 1 (S1) and overlay mix O1b. Here, the moisture condition negatively impacted the bond strength and was displayed in the bond failure location.

- In general, the best bonds are achieved when the substrate moisture condition is in the dry state and a workable overlay mix is applied. The failure surface is generally rough and represents strong mechanical interlock between overlay and substrate.

- In an attempt to maximise the bond strength of a low to moderate strength (20 – 50 MPa) concrete repaired member, the overlay concrete should always be a small percentage greater in strength than the substrate. This will ensure that the repaired member will not prematurely fail in the overlay, and hence greater bond strength achieved. Premature failure was experienced when the weak 25 MPa overlay was applied to the strong 50 MPa substrate. Here, the bond failure location was shallow and portrayed no substantial mechanical interlock.

The above descriptive results provided insight into the mechanics of bonded concrete overlays and how the bond strength of repaired concrete specimen was related to substrate moisture preparation, overlay strength and workability, and substrate strength. The next section in the results chapter provides a greater understanding of how the above mentioned factors affect the bond strength both individually and collectively. The factors are then ranked accordingly by their influence on bond strength.

4.5 Factorial Analysis

A full factorial analysis was carried out on the experimental results with the inclusion of an analysis of variance (ANOVA). This particular analysis was utilised to interpret the effects of multiple variables (i.e. moisture condition, overlay strength and overlay workability) on a single response (bond strength). This was a necessary analysis to perform as the variables influencing the bond strength were not acting in isolation, but rather collectively. The ANOVA provided insight into whether the different variables had a significant relationship with each other and if so, which variable was responsible for the greatest change in bond strength.

The ANOVA was carried out on the results with three assumptions:

- The population sample was normally distributed.
- The observations were independent of each other (i.e. moisture, strength, workability).
- The variance within each of the different factors is equal.

4.5.1 ANOVA test method and results

The ANOVA test is a statistical method used to test the difference between two or more means (three in this investigation) within an experiment, in order to determine whether the results obtained are statistically significant. The way in which the ANOVA determines whether the tested variables provide significant results is by rejecting the imposed null hypothesis. The null hypothesis imposed in this investigation, and hence the applied ANOVA, states that there are no differences in the means of the different variables tested and therefore the variation in results are by chance rather than the effects of the tested variables. Therefore, depending on the ANOVA results obtained, further analysis can be carried out in the form of a factorial analysis.

A full three-way ANOVA test was performed with the same data as in the descriptive results (excluding outliers) on MATLAB. The three variables which were tested for statistical significance were the overlay workability and strength, and the substrate moisture condition. This test was performed on all three substrates separately. In order for the null hypothesis to be rejected, the level of significance represented in table 4.3 (Prob>F) needed to be above 5% (0.05). This was the case in all three substrates when isolating the factors and in the majority of the interactions between them. This provided added incentive to perform a factorial design on the results to establish how the independent factors effect bond strength in isolation and collectively.

The ANOVA results are provided in table 4.3 with Sum of squares (Sum Squ.), degrees of freedom (DF), mean of squares (Mn Squ) as well as the F value and corresponding p-value (Prob>F)

Table 4.3: ANOVA results

Substrate 1					
Source	Sum Squ.	DF	Mn Squ.	F	Prob > F
X1	3.2576	3	1.0859	2.37	0.0769
X2	27.6194	1	27.6194	60.32	0
X3	0.017	1	0.0170	0.04	0.8478
X1*X2	0.1561	3	0.0520	0.11	0.9519
X1*X3	0.9565	3	0.3188	0.70	0.5571
X2*X3	0.0786	1	0.0786	0.17	0.6798
X1*X2*X3	2.2995	3	0.7665	1.67	0.1796
Error	35.258	77	0.4579		
Total	70.9904	92			
Substrate 2					
Source	Sum Squ.	DF	Mn Squ.	F	Prob > F
X1	6.1573	3	2.0524	4.27	0.0076
X2	0.1662	1	0.1662	0.35	0.5578
X3	0.0299	1	0.0299	0.06	0.8034
X1*X2	2.1378	3	0.7126	1.49	0.225
X1*X3	1.5886	3	0.5295	1.10	0.3527
X2*X3	6.8522	1	6.8522	14.28	0.0003
X1*X2*X3	6.8289	3	2.2763	4.74	0.0043
Error	37.4212	78	0.4798		
Total	61.8353	93			
substrate 3					
Source	Sum Squ.	DF	Mn Squ.	F	Prob > F
X1	2.4734	3	0.8245	3.27	0.0258
X2	0.5275	1	0.5275	2.09	0.1523
X3	0.0724	1	0.0724	0.29	0.5938
X1*X2	3.6878	3	1.2293	4.87	0.0038
X1*X3	2.3751	3	0.7917	3.14	0.0302
X2*X3	0.9945	1	0.9945	3.94	0.0507
X1*X2*X3	1.9596	3	0.6532	2.59	0.0591
Error	19.1774	76	0.2523		
Total	31.4777	91			

Source	Description
X1	Substrate Moisture
X2	Overlay Strength
X3	Overlay Workability
X1*X2	Combination of moisture and strength
X1*X3	Combination of moisture and workability
X2*X3	Combination of strength and workability
X1*X2*X3	Combination of all three factors

The factorial analysis was split into three different stages:

1. Eliminate outliers and determine with the use of ANOVA, whether the data representing the different factors affecting the bond strength are statistically significant.

2. Perform a main effects plot through a factorial design. This determines how each factor together with the level of treatments affects the bond strength. This was performed for each substrate, creating nine separate responses. (A treatment is regarded as a variable within the factor i.e. the overlay strength has two treatments: 25 MPa and 40 MPa)

3. Create two-way interaction plots of the three different factors.

4.5.2 Main effects plot

A "main effect" is regarded as the effect of one independent variable on the response of the dependent variable, while ignoring the effects of the other independent variables present. Therefore for each tested substrate, the effects of the tested variables on bond strength are analysed in isolation. For instance, in order to calculate how overlay workability affected bond strength, all the tested specimens which were subjected to either a 30 or 120 mm workable mix irrespective of overlay strength and substrate moisture preparation, were averaged to obtain a mean bond strength. The mean bond strength is then plotted against the number of treatments each variable has. For overlay workability, the number of treatments is two (see point number 2 above). Therefore the mean bond strength for each overlay workability treatment comprised of 8 different values ((4 moisture) x (2 strength)). This was the same procedure for calculating the main effects plot for the other two variables. This particular factorial design is very powerful in determining the extent of how each factor influences bond strength.

Three different main effects plots were created for each substrate, namely: Overlay strength, workability and substrate moisture condition. The description of the level of treatments together with the analysis is provided below.

- Overlay strength: Number of treatments = 2 – [1 2], where 1 = 25 MPa strength and 2 = 40 MPa strength, (mean bond strength per treatment = 8 values)

- Workability of the Overlay: Number of treatments = 2 – [1 2], where 1 = 30 mm slump and 2 = 120 mm slump, (mean bond strength per treatment = 8 values)

- Moisture condition of substrate surface: Number of treatments = 4 – [1 2 3 4], where 1 = Saturated surface dry (24 hours), 2 = Saturated surface dry (30 min), 3 = Ambient room temperature (7 days) and 4 = Oven dried at 50°C (24 min), (mean bond strength per treatment = 4 values)

Substrate 1:

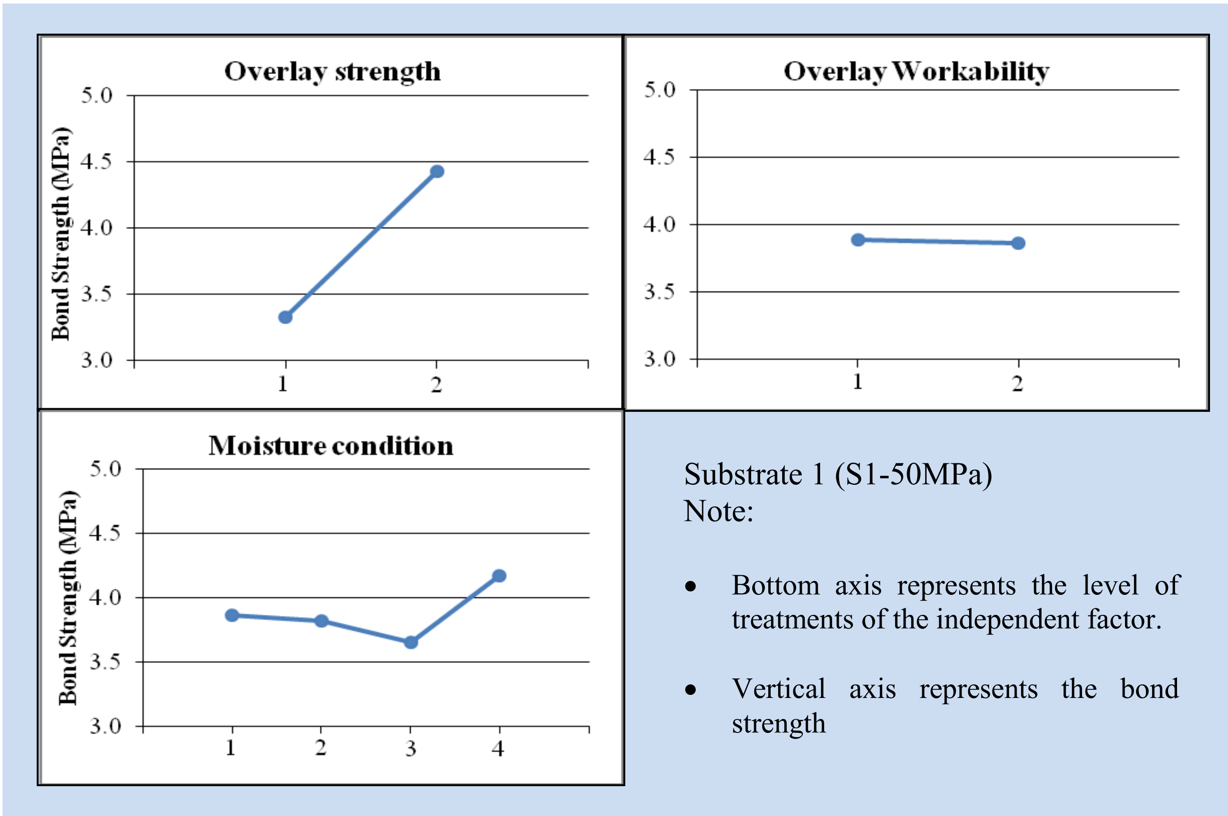


Figure 4.21: Main effect plots of substrate 1

As seen in figure 4.21 the main effect slopes of the workability and moisture condition are minimal when compared with the change in overlay strength. A number of factors can be attributed to this result; however the reason is primarily based on the compatibility issue. The overlay strength provides a huge jump in bond strength when shifted from 25 to 40 MPa, as the overlay is now in the same strength range as the substrate, allowing the bond strength to reach its full strength value. When the overlay was only 25 MPa, lower bond strengths were obtained due to bond failing in the weak overlay-interface zone.

Other than the increase in bond strength achieved when oven drying the substrate prior to casting, the workability of the overlay and moisture condition of the substrate provided no substantial influence on bond strength for substrate 1. This can again be attributed to the concrete characteristics of the substrate concrete; substrate 1 is relatively impermeable and has a low water sorptivity value as mentioned in section 3.5.2 The added workability of the mix was not able to influence the interaction between the new and old concrete. However when the substrate was dried out, this provided an adequate amount of open pores to allow for a better mechanical interlock.

Substrate 2:

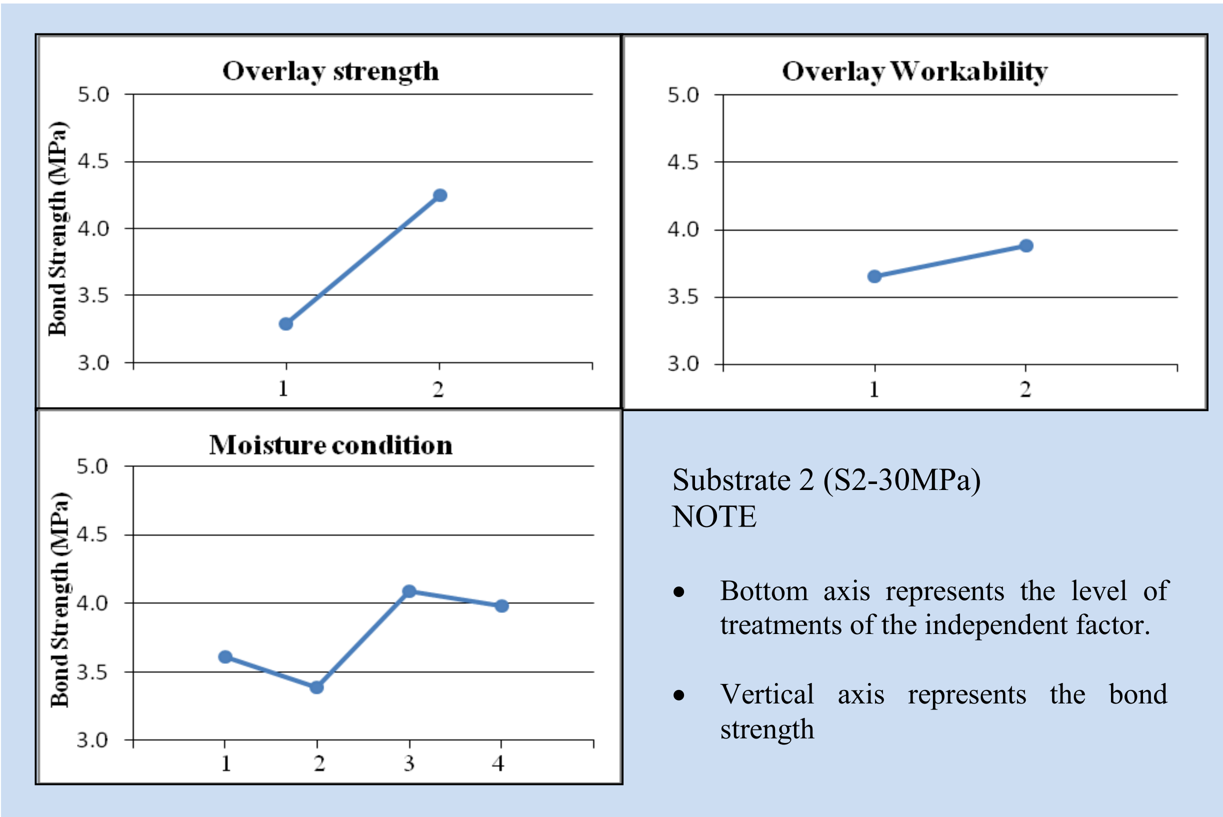


Figure 4.22: Main effect plots of substrate 2

The 'main effect' results obtained from substrate 2 illustrate how all three factors influence the bond strength of the repaired specimen. Not only did the overlay strength provide for greater bond, but as the workability of the overlay mix was increased, the repaired specimen responded in a positive manner.

One of the more interesting observations was the influence of the moisture condition on the bond strength. The main effect plot illustrates an increase in the bond capacity of the repaired member as the substrate tends to a drier state. The max bond was achieved when the substrate was exposed to ambient room temperatures as in the creep room, before applying the overlay. The added influence of the workability and moisture condition of the substrate can be attributed to the change in substrate properties from a more impermeable and strong substrate found in 1 to a less impermeable and hence more penetrable concrete of substrate 2.

Substrate 3:

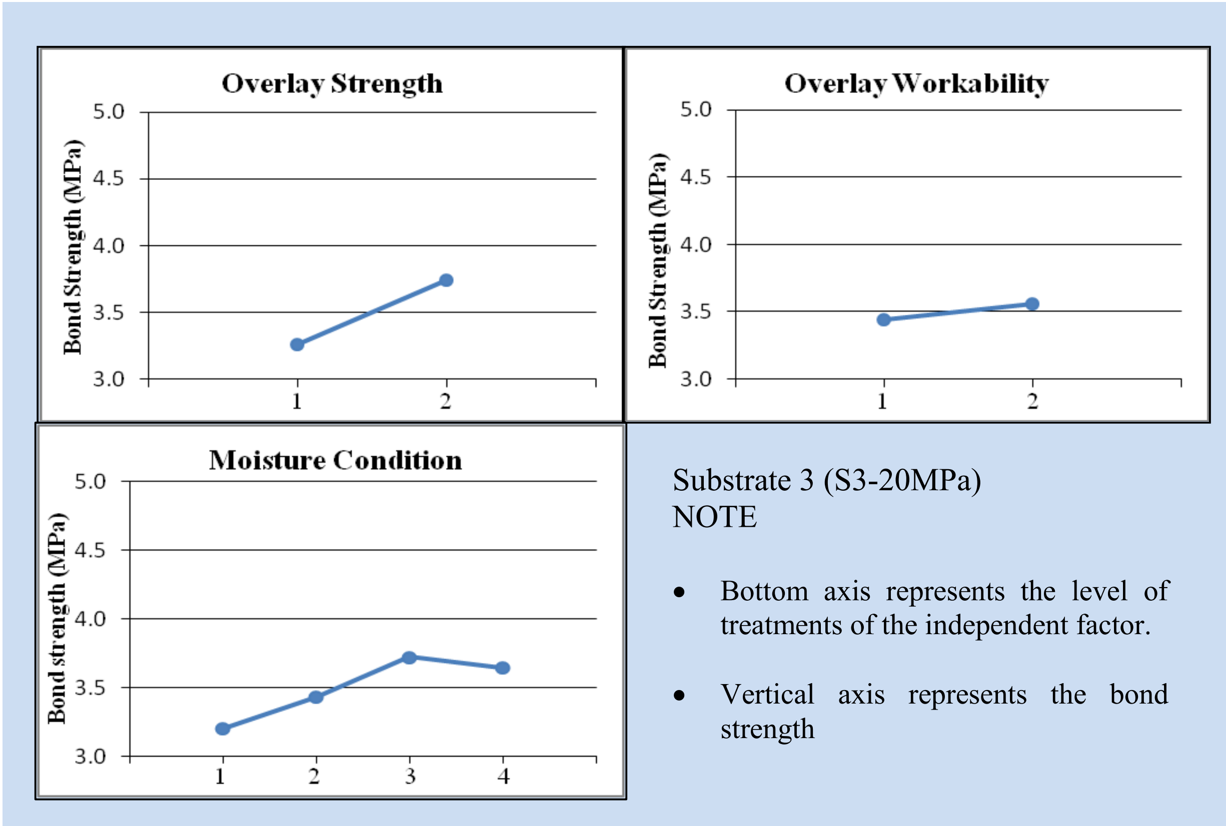


Figure 4.23: Main effect plots of substrate 3

From figure 4.23, it can again be seen that the overlay strength has a greater influence on the bond strength, than the other two tested factors. The main effect plot indicates that a better bond will be achieved when a repair mortar with a higher strength is used for the overlay. Furthermore, the workability of the concrete overlay, as well as substrate moisture preparation, represented an upward trend when the workability increased and the moisture preparation tended to a drier state. The added influence of these two factors can again be brought back to the substrate properties. Substrate 3 represents a poor grade of concrete with many voids. The workable overlay mix and dry substrate take advantage of the open pore structure and thus provide better mechanical interlock.

When the effect of different substrate moisture conditions was compared, it could be seen that higher bond strengths were achieved when the substrate was in a dry state. The highest bond strengths were recorded when the substrate surface was exposed to ambient room temperatures (creep room), whereas the weakest values were achieved when the substrate surface was exposed to pre-wetting for 24 hours prior to casting.

To provide a better understanding on how the three factors were influenced by the different substrates. The main effect plots were superimposed with one another. Figure 4.24 illustrates the end result.

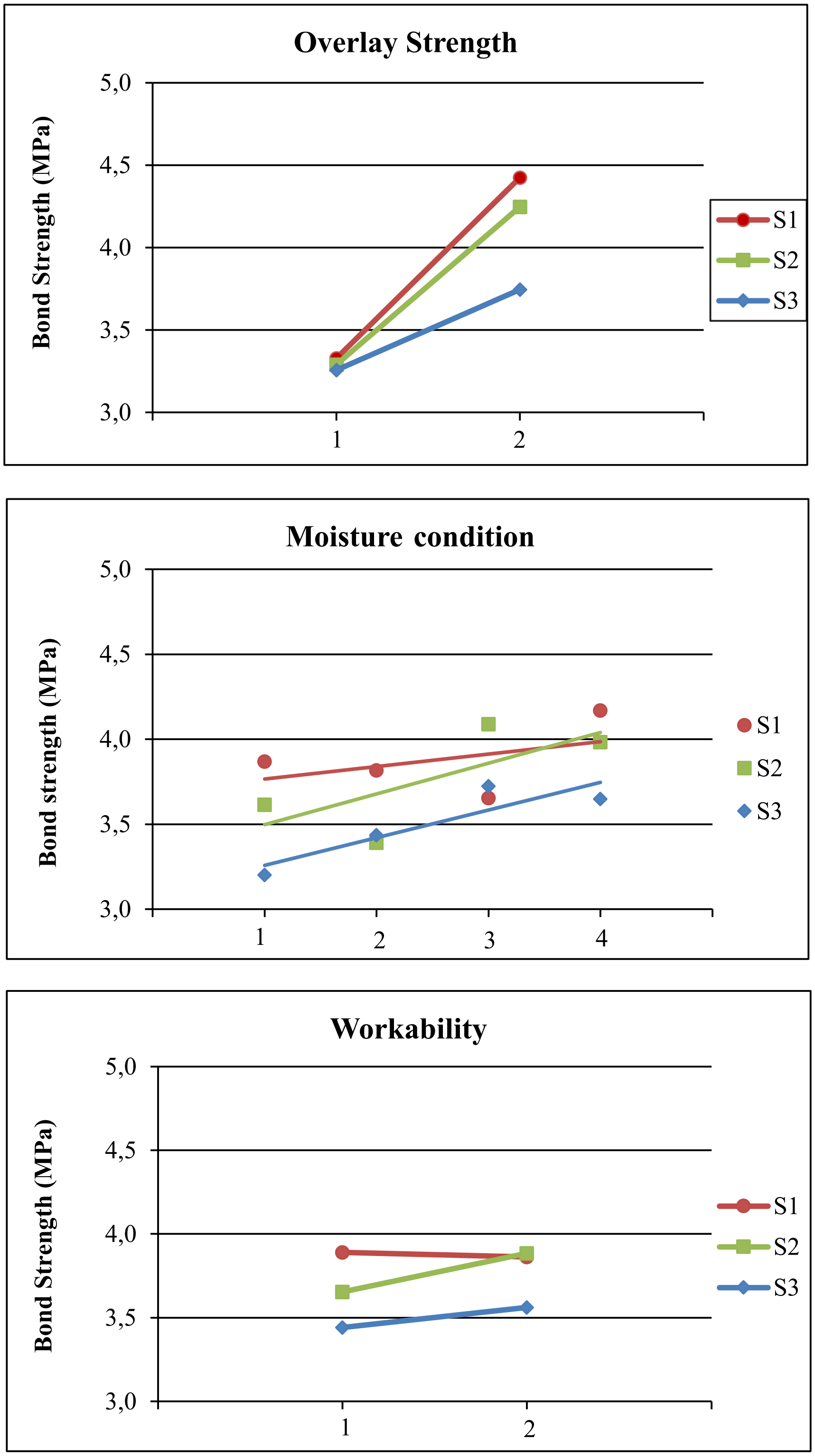


Figure 4.24: Comparison of main effects plots for different substrates

From the above figure, it is clear that overlay strength affects the bond between existing and new concrete substantially and represents a steep upward trend as the overlay increases in strength. The fact that the bond strength was very similar across all substrates when the weaker overlay was utilised reiterates how repaired concrete members will always fail in the weaker member. The weak overlay mix neutralised the positive effect of the stronger substrates by generating a weak overlay interface zone and thus resulted in substrate 1 and 2 producing similar bond strength results to substrate 3.

The effect of altering the workability of the overlay mix produced no substantial change in bond strength. There was a slight upward trend; however the gradient of the increase was not large enough to provide evidence of bond strength improvement. One of the possibilities for the inconclusive result was the effect of the compaction process of the overlay during casting as well as substrate concrete properties. Refer to section 4.2.1 for the discussion in this regard.

The three substrates when analysed according to moisture condition, illustrated a general trend to increase bond strength as the substrate surface went from a wet to dry state prior to casting. This trend, depicted in figure 4.24, provides valid evidence of how preparing substrates in a SSD creates no increase in bond strength and in many cases reduces the bond capacity of the repaired member. One needs to keep in mind that the moisture conditions which the substrates were subjected to were implemented in a laboratory under controlled conditions. Site conditions might lead to the presence of free standing water on the substrate before casting and reduce bond potential substantially.

To further breakdown the influence of substrate moisture preparation on bond strength, as well as overlay strength and workability, two-way interaction plots were developed for each substrate and are presented below.

4.5.3 Interaction plots

Interactions occur within an experiment when the effect of a factor on the response (i.e. bond strength in this case) differs as the level of treatment of another independent factor changes. Figures 4.25 – 4.27 represent two-way interactions of the three variables being tested for each substrate. The way in which the bond strength values were calculated for each independent factor is similar to the main effects plots. For instance, when determining how the overlay strength interacts with workability, the calculated bond strength when the overlay strength was at its first treatment level (i.e. 25MPa) was compared to the overlay workability at 30 and 120 mm slump. This illustrates how the 25 MPa overlay mix reacted when the workability changed, but does not take into account changes in moisture condition. Hence each point on the interaction plot for overlay strength and workability consists of an average of 4 bond values. The same process was carried out when constructing the interaction between overlay strength – substrate moisture condition and overlay workability – substrate moisture condition.

In the interaction plots, the y-axis again represents the bond strength, where as the x-axis represents the level of the variable being analysed. Each graph is represented by two curves. This illustrates the interaction between the two variables. The two blocks represented on the right hand side of the interaction plots indicate the different treatment levels of the curves, whereas the headings on the plot area represent the interaction between them. For instance, graph A in figure 4.25 shows the interaction between overlay strength and workability. The solid curve represents the weak overlay mix (25 MPa) and the dashed curve represents the strong overlay mix (40 MPa). The level of treatments on the x-axis (1, 2) identifies which workability state the overlay mix was in prior to casting. It should be note that these interactions are dependent on the characteristics of the three different substrates utilised for these experiments.

Substrate 1:

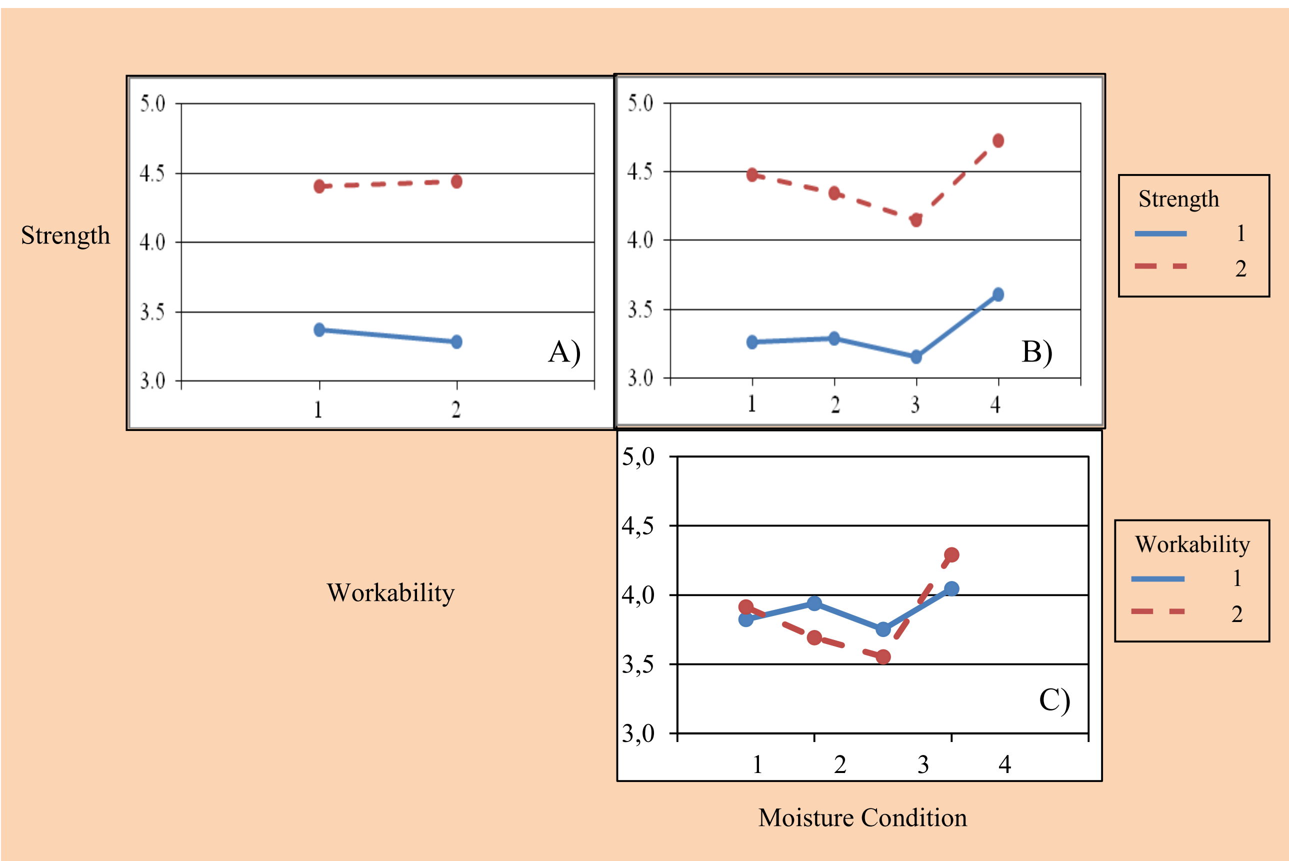


Figure 4.25: Interaction plots for substrate 1

The graphs A and B confirm the positive main effect of overlay strength on the repaired specimen for substrate 1, together with how the increase in overlay workability from A, favours this increase in strength over a weaker overlay. The interaction of the moisture condition with the overlay strength was very similar and illustrated a net increase in bond strength as the substrate was exposed to dry conditions.

There was a strong interaction between the workability and moisture condition of the repaired specimen represented in graph C. As the workability of the overlay mix increased, so did the impact of the substrate moisture condition. The workable overlay mix preferred a substrate which was in a dry state; however the stiff overlay mix has no substantial preference.

Substrate 2:

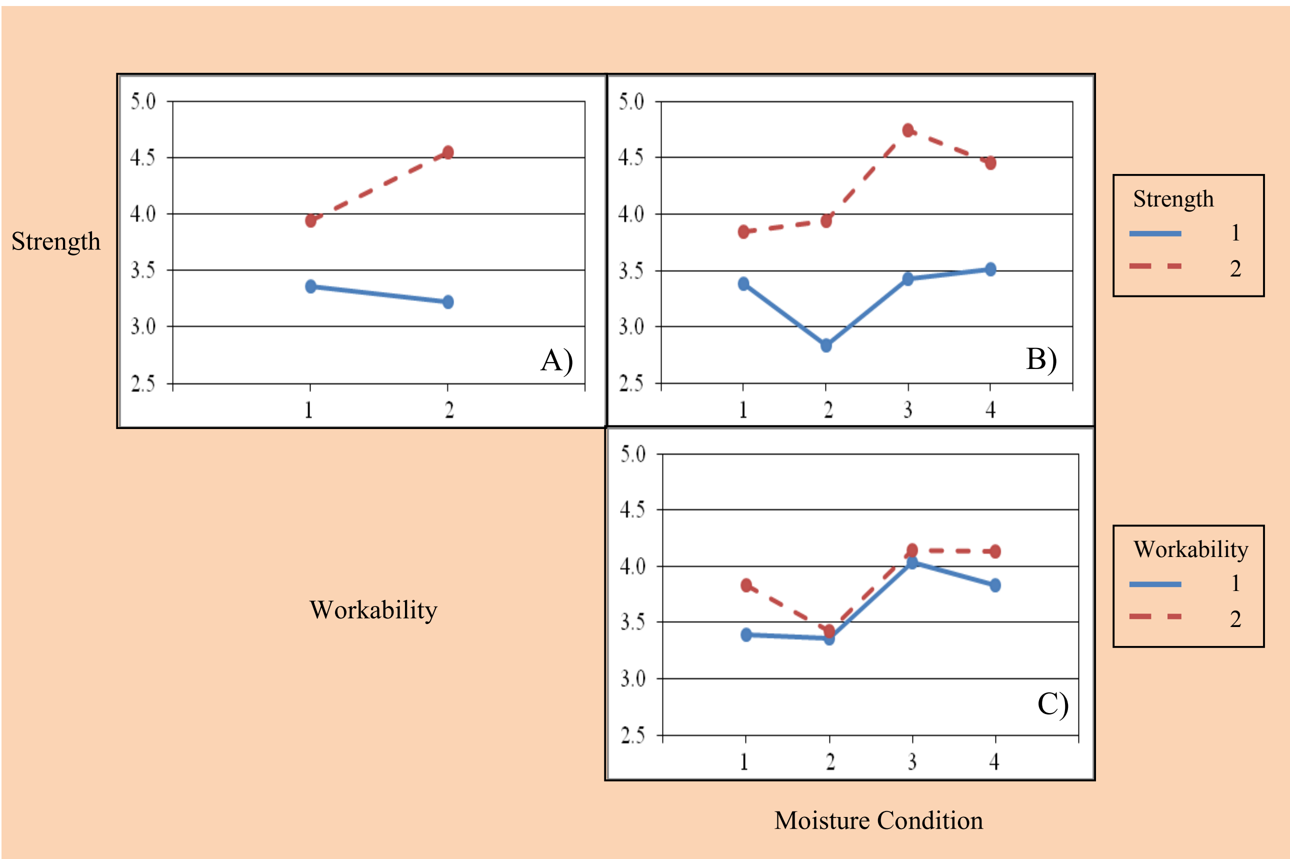


Figure 4.26: Interaction plots for substrate 2

The interaction between overlay strength and overlay workability found in graph A was more pronounced than previously witnessed with substrate 1 and suggests that there is a strong relationship between these two variables. Graph A illustrates that as the strength of the overlay increases, the bond strength is positively influenced with an increase in workability. Conversely, if a lower overlay strength is utilised, the increase in workability nominally decreases the bond strength experienced by the repaired member.

The graphs B and C show a very slight increase in bond strength of the repaired member under increasing values of strength-moisture condition and workability-moisture condition. In both cases the interaction of these variables were not as strong as in graph A, but does show an interaction nevertheless. It can be concluded that the effect of moisture condition of the substrate is more pronounced with a strong/workable overlay mix, when the substrate concrete exhibits characteristics as seen with substrate 2

Substrate 3:

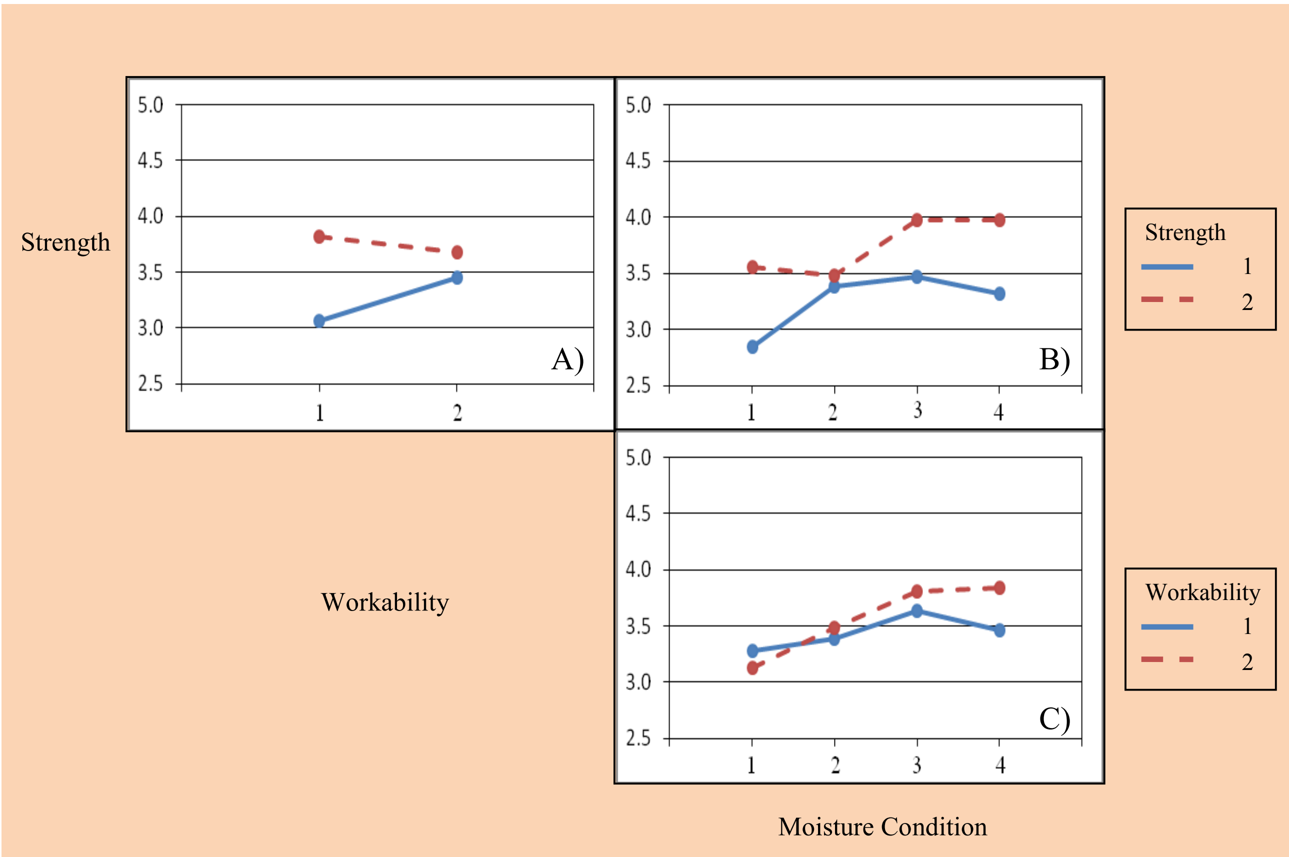


Figure 4.27: Interaction plots for substrate 3

Graph A for substrate 3 illustrated a change in trend from the first two stronger tested substrates above. The bond strength of the repaired member decreased as the overlay mix with the higher strength shifted to a higher workability, conversely the bond strength increased when the lower strength overlay moved to a higher workable level. Although the above mentioned factors were witnessed, the bond strength was still higher when utilising the stronger overlay mix. However one must be careful of disregarding this result, as an overlay mix which is even further increased in strength, may produce bond strengths which deteriorate far more rapidly than the one illustrated above.

The interactions illustrated in graph B and C are fairly similar to the previous two substrates; however the strength of the overlay does not provide as much of an increase in bond strength as previously experienced. A positive interaction was witnessed between the overlay strength and moisture condition, as well as the workability and moisture condition of the substrate as the level of the different factors increased. Therefore, one can conclude that for a substrate of this composition, that the moisture condition of the substrate plays a significant role in influencing bond strength.

The aforementioned interaction plots of the three independent variables and substrates have produced interesting results which contradict how many engineering repair measures are currently being implemented. Although the tested specimens do represent an isolated case, the degree in which these tested factors influenced the bond strength cannot be ignored. In order to quantify the results obtained from both the qualitative and quantitative experimental analysis, figure 4.28 was created in the next section which lists the importance of the different tested factors which influence bond strength.

4.6 The importance of tested variables on bond strength

This section will rank each of the different variables (moisture preparation, overlay strength and overlay workability) which were tested on the repaired specimens, in an attempt to establish which variables, if altered between the different levels tested, require the greatest amount of consideration when utilising a specific concrete substrate. The figures were split according to the three different substrates, as the influence of the tested variables differ as the substrate composition changes.

The performances of the tested variables were compared to theoretical values obtained from various other experimental work performed in the same field (Beushausen & Alexander, 2009). The tested variables were ranked out of three, with three representing a level of high importance and 1 the lowest level of importance. The way in which the level of importance for each of the different variables was established, was through the factorial analysis (both main effects and interaction plots were considered). I.e. if you had to change the variable (moisture wet – dry) will this impact on the bond strength.

The results obtained from substrate 1 led to the formulation of figure 4.28 A). It is clear that the variable which influenced bond the most and hence has the highest level of importance (three) in this situation is the Overlay Strength (OS). This was followed by both the Moisture Condition of the Substrate (MCS) and Overlay Workability (OW) with a level of importance of one. When compared to the theoretical values, the OS was more highly regarded as a variable which would influence bond strength, whereas OW and MCS was deemed to not affect bond strength as much as previous experiments. Figure 4.24 provides experimental evidence for the aforementioned importance levels.

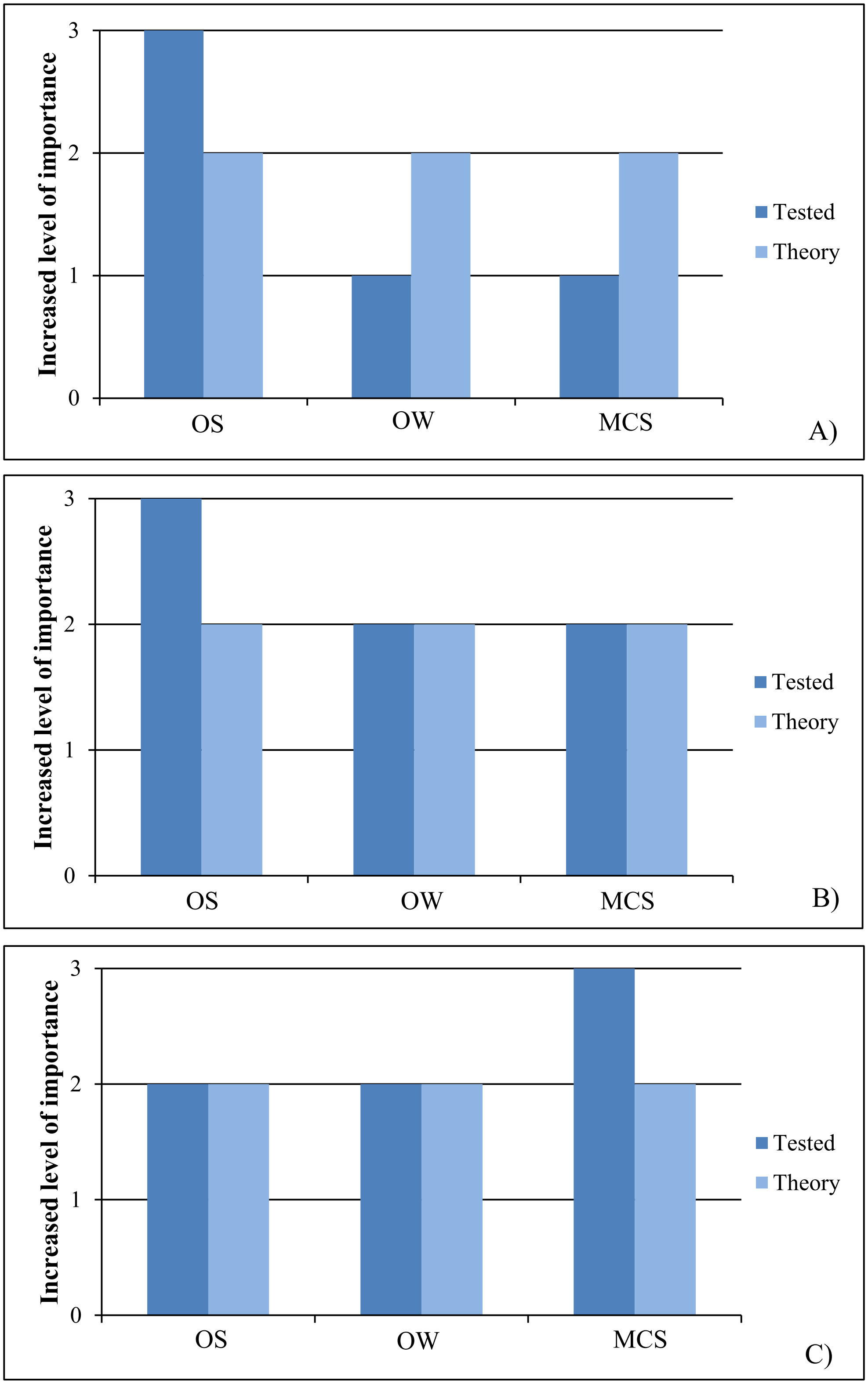


Figure 4.28: Level of importance A) substrate 1, B) substrate 2, C) substrate 3

Figure 4.28 B) was established by taking into the account the different bond strengths achieved for substrate 2. From the results it was concluded that OS was again the variable which provided the greatest change in bond strength and hence received an importance level of three. This was followed by both OW and MCS with an importance level of two. When comparing these results to the theoretical values, it was noted that both the OW and MCS received identical values, whereas the tested OS was one level of importance point ahead.

Substrate 3 provided results in section 4.5 where the substrate moisture condition influenced the bond strength by a considerable amount. The degree of bond influence for overlay strength and workability was not as substantial as previously experienced in substrate 1 and 2. As a result figure 4.28 C) rated all of the variables with an importance level of two, excluding moisture preparation of the substrate.

From figures 4.28 A), B) and C) it can be seen how the different variables interact with each other as well as in isolation to create better bond, is largely dependent on the substrate composition. Substrate 1 was strong and impervious. This resulted in a high demand for a strong overlay in order to create a strong bond. The impervious structure of the substrate also did not allow the workability of the overlay and moisture condition of the substrate to have any substantial impact. Substrate 2 was relatively strong, but was more penetrable than substrate 1. Here, the workability of the overlay could now assist with mechanical interlock, provided that the substrate moisture condition was in a dry state. Again the increase in overlay strength substantially increased bond. Substrate 3 was designed to replicate a poor grade of concrete. Therefore, the substrate was weak and very porous. The porous nature of the substrate allowed for the workable overlay mix to create a better mechanical interlock provided that the substrate was in a dry state. This greatly influenced bond strength and as a result achieved an importance rating of 3.

Section 4.7 will provide a comparison of how common engineering practice differs from what the results from this particular investigation recommend, and how these results tie up with previous research.

4.7 Common engineering practice and lab results

This section aims to identify the differences between the results obtained from this investigation and repair practices performed on site. The site repair techniques shall be analysed and then compared to laboratory investigations, with the findings establishing a set of conclusions and recommendations.

Site concrete repair practice

Due to the different types of concrete deterioration which is experienced on concrete structures, there are many types of concrete repair processes and techniques which are utilised to best suit the problem at hand. The procedure which was analysed in this section was the concrete bonded overlay repair process. Here great detail was addressed to substrate preparation and overlay application. The general repair process is described below.

Substrate preparation and overlay application as on site

- Rid the substrate of any deteriorated concrete and roughen the surface by either sandblasting, water jetting or any other appropriate method without creating any micro-cracks.

- Clean the substrate concrete of any leftover debris from the roughening technique utilised. This can be performed with either water or air pumps.

- Ensure that the substrate is in <u>a saturated surface dry state</u> prior to the application of the overlay.

- Apply the repair mortar on the target substrate ensuring proper compaction in order to achieve maximum bond.

The aforementioned concrete repair application process has become a fairly standardised and internationally recognised approach in addressing concrete deterioration with respect to bonded overlay application; however, if one had to compare how the substrate is prepared with respect to moisture and the results obtained in this particular investigation, certain doubts arise on whether maximum bond is achieved.

In section 4.2 and 4.5 it is clear that there is a positive trend with an increase in bond strength as the substrate concrete tendered towards a drier state. This was noticed across all three different tested substrates, irrespective of overlay characteristics. Furthermore, these experiments were carried out in laboratory environments, where testing conditions are kept constant. It will also not be uncommon for the substrate to have free standing water present prior to application of the overlay when on site. This will further reduce bond strength as mentioned in the literature, section 2.6.4.1 (graph on moisture, figure 2.18). Therefore, the common substrate preparation method followed on site, may be incorrect in terms of moisture condition of the substrate. From the results obtained and the observations made, a set of conclusions and recommendations are presented.

5. Summary, Conclusions and Recommendations

5.1 Introduction

The concrete repair industry has grown substantially over the last decade with the ambition to meet the ever increasing demand of structures either deteriorating prematurely or reaching the end of their design life. Bonded concrete overlays remain the main tool in the repair process of concrete structures and as a result are widely utilised across the world. The popularity of the repair process includes the ability of the bonded overlay to be used for a number of applications whilst still being fairly simple to apply. The bonded overlay and substrate act as a composite system in order to restore the service life of the structure and hence its functionality.

There are often many factors which affect the performance of the bonded overlay and include: Substrate preparation, overlay properties and differential shrinkage between overlay and substrate. Substrate preparation before the application of the overlay is of paramount importance in order to achieve a strong bond and is often neglected. One particular facet which still induces confusion within its application is the impact of moisture preparation of the substrate.

The effect of moisture preparation of the substrate surface prior to overlay application is something which has not been completely understood by contractors and engineers alike. The basic interpretation of this particular surface preparation measure is that the substrate should be in a saturated surface dry state to achieve the best possible bond between substrate and overlay. However many researchers including Zhu (1992), Silfwerbrand (2003) and Beushausen (2010) have performed experimental tests which are in contrast to current understanding.

The moisture on the substrate has the ability to reduce bond strength, depending on the type of overlay mix utilised, by filling all the pores within the concrete and thus preventing strong mechanical interlock between substrate and overlay. The overlay mix is prevented from interacting with the substrate and thus creates a weak concrete layer directly above the interface. This is known as the overlay interface zone.

The investigation in this study serves as a measure in which the effects of moisture preparation of the substrate are quantified in terms of bond strength. The results provided valuable information in terms of what substrate moisture condition is required in order to maximise bond strength for a particular substrate and overlay (strength and workability). The aforementioned concrete properties were selected based on common concrete repair mixes and previous studies.

5.2 Summary of main conclusions

In general, the bond strength of the repaired specimen was sensitive to substrate moisture preparation and the interaction of the aforementioned with substrate strength, and overlay strength and workability. Below the main conclusions of the different varied parameters are discussed.

Substrate moisture preparation and bond strength

The repaired specimen experienced an increase in bond strength as the moisture preparation shifted from the recommended saturated surface dry (SSD) state to a dry surface condition. This was noticeable across all three substrates and contradicts common practice techniques which are implemented with respect to bonded overlays. Although there was this upward trend in bond strength, only two experimental cases provided a statistical result where the substrate in a SSD state was responsible for the decrease in bond strength (section 4.2). In some cases the increase in bond strength was minimal and can be attributed to the interaction of the different parameters which were being tested. The influence of moisture preparation was more pronounced as the strength grade of the substrate decreased i.e. weaker, poorer substrates are more sensitive and vulnerable to moisture state. This was attributed to the sorptivity and permeability characteristics of the substrate.

Therefore, from the results, it was clear that substrate moisture preparation provides no increase in bond strength and in some instances, can compromise the bond of the composite member.

Influence of substrate strength

Although the substrate strength did not directly impact the bond strength in terms of moisture preparation, the added strength did allow for the repaired specimens to achieve higher bond strengths. The increase in substrate strength provided a platform which allowed the bond to reach its full potential before failure i.e. the weaker concrete would fail prematurely in the substrate and thus reduce bond strength if the overlay was of a higher strength grade.

Influence of overlay strength

The influence of overlay strength on the bond of the repaired specimen was similar to that of the above mentioned substrate. The increase in strength resulted in the increase of bond strength. However, the degree in which the bond strength increased was governed by the existing strength of the substrate. If the overlay overpowered the substrate, the bond strength would not reach its full potential (vice versa). Therefore, strength compatibility of the two different concrete components within a repaired member is of great importance. The strength of the substrate together with sorptivity and porosity should be measured in order to properly design for the repair.

Influence of overlay workability

The overlay workability, in isolation, did not substantially influence the bond strength of the composite specimen. The reason can be partly explained through the compaction process which was incorporated into the investigation (section 3.6). However, the workability did provide a greater than 50% confidence in variability of bond strength due to the overlay either comprising of a 30 or 120 mm slump. Generally the more workable mix achieved higher bond strength results; however this was when the substrate was in a dry condition. When the substrate was exposed to a saturated surface dry moisture condition, the stiff overlay mix (30mm) often achieved similar and in some cases higher bond strengths than if the overlay mix was highly workable (120mm). This was generally the case in the testing of the strongest substrate (S1). Here the substrate properties such as sorptivity, absorption and permeability restricted the interaction of the workable mix and the pore structure of the substrate under saturated surface dry conditions. The same was observed for the weaker substrates (S2 and S3), but the change in bond strength was not as extensive.

Interactions of the varied parameters

The bonded concrete overlay is a complex problem with many variables interacting in conjunction with each other. The performance of the overall bond strength is dependent on how the different variables respond to each other in the environment in which they find themselves in. For instance a substrate which is in a dry condition will more than likely produce a stronger bond with a workable overlay than a stiff overlay mix. The same can't entirely be said for the reverse situation, although there were instances where this was the case. Substrates which were relatively impenetrable displayed weaker bond strengths when the workable 120mm slump overlay was applied to a substrate in a SSD state than the 30 mm mix. Therefore there is no "best way" to apply the bonded overlay technique for all situations, but rather requires the input of the engineer to evaluate the different parameters present and make a technical decision based on his findings.

Bond failure locations

The bond failure location of a composite member provides great insight into how strong and compatible the bond was between the new and old concrete. From this particular investigation it can be concluded that bond failure locations showed better surface properties of strong mechanical interlock when the substrate was in a dry state and a workable overlay mix applied. These observations generally resulted in a higher bond strength being achieved. Conversely, when the substrate was exposed to pre-wetting, the bond failure location was generally smoother and did not display any deep penetration of the overlay into the substrate.

5.3 Recommendations

This investigation identifies some of the main factors which influence the bond strength of bonded overlays, with special reference to the impact of moisture condition of the substrate surface prior to overlay casting; however further testing is still required in order to attain a deeper understanding of the fundamentals of the bonded overlay repair technique. Below recommendations for engineering practice and further experimental work are provided.

5.3.1 Bonded overlay application

From the conclusions drawn with respect to the experimental work performed on the bonded overlay in this investigation. The following recommendations are proposed to engineers when utilising the bonded overlay repair method:

- Identify the mix and mechanical properties of the existing substrate i.e. concrete composition, sorptivity, permeability and substrate strength. This will provide the necessary information to decide what type of repair mortar is required and whether moisture preparation of the substrate is necessary (from the investigation, the substrate should be left in the dry state if a workable overlay mix is utilised. This provides stronger and more consistent results)

- The strength of the overlay mix should always be a small percentage greater than the substrate concrete. This will ensure that the bond reaches full strength capacity and will not prematurely fail in the overlay.

- Ensure that the substrate is clean of all dust and damaged concrete from roughening techniques utilised prior to casting. Pre-wetting the substrate is not required and may lead to lower bond strengths.

- Although the effect of compaction was not tested, this is an important step in achieving a lasting bond between substrate and overlay, and thus suitable measures should be implemented to ensure appropriate compaction.

- Lastly, curing of the repaired member is of importance to ensure strength gain at the interface zone between substrate and overlay.

5.3.2 Experimental work

There are many different factors which can influence the effectiveness of bonded concrete overlay repairs and although many were tested in this investigation, there are many more characteristics which still need to be investigated to create a better understanding of this particular repair method. The following aspects should be considered:

- The effects of intermediate moisture conditions within the substrate and its influence on bond strength i.e. in between a SSD and dry state.

- The comparison of bond strength increase and differential shrinkage between overlay and substrate while varying substrate moisture conditions.

- The influence of overlay compaction and substrate moisture preparation on bond strength.

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Appendix A – Bond strength results

Note: CM is the concrete mould which was used for the overlay application.

Substrate (S)	Moisture Prep (M)	Overlay (O)	Date of Cast	date for curing	date for testing	Bond Strength Results -BS (KN)					
						BS 1	BS 2	BS3	BS4	BS5	BS6
S1	M1	O1a	29/04/2013	30/04 - 27/05	27/05/2013	117.5	97.5	62.5	111.0	122.0	78.0
CM1	SSD 1 (wet for 24 hours)	O1b	29/04/2013	30/04 - 27/05	27/05/2013	91.0	98.5	112.0	120.0	117.0	81.0
CM3		O2a	29/04/2013	30/04 - 27/05	27/05/2013	56.0	63.5	86.0	86.5	75.0	76.5
CM1		O2b	30/04/2013	1/05 - 28/05	28/05/2013	60.0	76.0	86.5	68.0	58.5	88.0
CM2	M2	O1a	30/04/2013	1/05 - 28/05	28/05/2013	67.5	114.5	95.0	107.0	79.5	112.0
CM3	SSD 2 (wet for 30 mins)	O1b	30/04/2013	1/05 - 28/05	28/05/2013	101.0	127.5	105.0	74.5	103.0	87.0
CM2		O2a	2/05/2013	3/05 - 30/05	30/05/2013	79.0	92.5	83.0	44.5	83.0	80.5
CM1		O2b	2/05/2013	3/05 - 30/05	30/05/2013	62.5	79.0	56.5	66.0	62.0	73.0
CM3	M3	O1a	2/05/2013	3/05 - 30/05	30/05/2013	106.0	104.0	95.0	106.5	89.0	104.0
CM4	Dry in room temp (creep room)	O1b	2/05/2013	3/05 - 30/05	30/05/2013	97.5	124.0	93.0	75.0	81.0	83.0
CM2		O2a	3/05/2013	4/05 - 31/05	31/05/2013	50.0	59.5	81.0	64.0	83.0	71.0
CM1		O2b	3/05/2013	4/05 - 31/05	31/05/2013	66.0	70.0	57.0	66.0	97.0	88.0
CM3	M4	O1a	5/05/2013	6/05 - 2/06	2/06/2013	106.0	105.0	106.5	96.0	105.0	93.5
CM4	oven dried - 50 (24 hours)	O1b	5/05/2013	6/05 - 2/06	2/06/2013	99.5	83.5	141.0	105.0	137.0	98.5
CM2		O2a	5/05/2013	6/05 - 2/06	2/06/2013	80.0	50.0	91.0	92.0	71.0	96.0
CM1		O2b	5/05/2013	6/05 - 2/06	2/06/2013	101.0	71.0	81.0	90.0	98.0	53.0

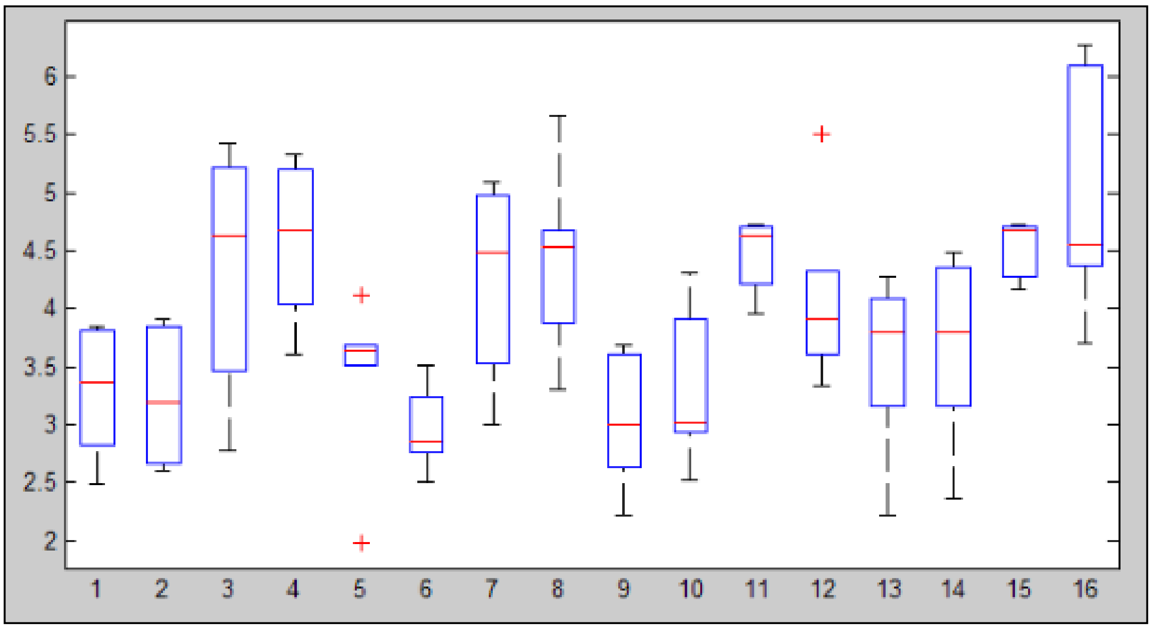
Substrate (S)	Moisture Prep (M)	Overlay (O)	Date of Cast	date for curing	date for testing	Bond Strength Results -BS (KN)					
						BS 1	BS 2	BS3	BS4	BS5	BS6
S2	M1	O1a	18/04/2013	19/04 - 16/05	16/05/2013	54.5	91.0	72.0	82.5	87.2	93.0
	SSD 1	O1b	18/04/2013	19/04 - 16/05	16/05/2013	115.5	89.5	72.5	85.5	96.5	98.0
	(wet for 24 hours)	O2a	19/04/2013	20/04 - 17/05	17/05/2013	91.3	58.5	89.5	79.5	56.5	60.0
CM3		O2b	21/04/2013	21/04 - 19/05	19/05/2013	82.3	92.5	60.0	67.5	90.0	86.0
CM2	M2	O1a	22/04/2013	23/04 - 20/05	20/05/2013	54.0	64.8	95.0	64.0	87.5	85.0
CM1	SSD 2	O1b	22/04/2013	23/04 - 20/05	20/05/2013	100.5	123.0	105.0	87.0	81.0	117.5
CM3	(wet for 30 mins)	O2a	22/04/2013	23/04 - 20/05	20/05/2013	84.5	52.5	89.5	77.0	86.0	66.5
CM2		O2b	23/04/2013	24/04 - 21/05	21/05/2013	80.0	81.5	75.7	73.5	60.0	95.0
CM1	M3	O1a	23/04/2013	24/04 - 21/05	21/05/2013	136.0	100.0	108.5	74.0	132.5	93.5
CM3	Dry in room temp	O1b	23/04/2103	24/04 - 21/05	21/05/2013	114.0	89.5	117.0	117.5	126.0	73.0
CM2	(creep room)	O2a	24/04/2013	25/04 - 22/05	22/05/2013	81.0	69.8	84.5	73.5	84.0	53.0
CM1		O2b	24/04/2013	25/04 - 22/05	22/05/2013	57.0	62.0	89.0	80.0	84.5	108.0
CM3	M4	O1a	24/04/2013	25/04 - 22/05	22/05/2013	119.0	102.0	80.0	89.5	98.5	66.0
CM2	oven dried - 50	O1b	25/04/2013	26/04 - 23/05	23/05/2013	129.0	104.5	97.5	88.5	126.0	103.0
CM1	(24 hours)	O2a	25/04/2013	26/04 - 23/05	23/05/2013	84.0	84.5	65.5	66.5	103.5	74.5
CM3		O2b	28/04/2013	29/04 - 26/05	26/05/2013	70.0	74.0	83.0	90.0	78.5	73.0

Substrate (S)	Moisture Prep (M)	Overlay (O)	Date of Cast	date for curing	date for testing	Bond Stregnth Results -BS (KN)					
						BS 1	BS 2	BS3	BS4	BS5	BS6
S3	M1	O1a	6/05/2013	7/05 - 3/06	3/06/2013	88.0	80.0	92.0	84.0	84.5	100.0
CM4	SSD 1	O1b	6/05/2013	7/05 - 3/06	3/06/2013	63.5	79.5	71.5	75.5	49.0	92.5
CM2	(wet for 24 hours)	O2a	6/05/2013	7/05 - 3/06	3/06/2013	53.0	65.0	72.0	51.5	51.0	63.5
CM1		O2b	6/05/2013	7/05 - 3/06	3/06/2013	75.5	67.5	93.5	73.5	66.0	61.0
CM3	M2	O1a	7/05/2013	8/05 - 4/06	4/06/2013	77.5	71.0	95.5	71.5	88.5	59.0
CM4	SSD 2	O1b	7/05/2013	8/05 - 4/06	4/06/2013	92.5	82.0	82.5	80.0	75.0	78.0
CM2	(wet for 30 mins)	O2a	7/05/2013	8/05 - 4/06	4/06/2013	88.0	55.0	65.5	74.0	78.0	91.0
CM1		O2b	7/05/2013	8/05 - 4/06	4/06/2013	84.0	94.0	87.0	59.0	63.0	76.0
CM3	M3	O1a	8/05/2013	9/05 - 5/06	5/06/2013	94.0	75.5	87.0	109.0	80.5	96.0
CM4	Dry in room temp	O1b	8/05/2013	9/05 - 5/06	5/06/2013	91.0	94.5	118.0	67.0	78.5	81.5
CM2	(creep room)	O2a	8/05/2013	9/05 - 5/06	5/06/2013	71.5	77.0	76.0	89.5	43.0	69.0
CM1		O2b	9/05/2013	10/05 - 6/06	6/06/2013	74.5	91.5	79.5	86.0	80.0	86.0
CM3	M4	O1a	9/05/2013	10/05 - 6/06	6/06/2013	96.0	109.0	84.5	87.0	70.0	81.5
CM4	oven dried - 50	O1b	9/05/2013	10/05 - 6/06	6/06/2013	98.0	93.5	75.0	93.5	98.5	86.0
CM2	(24 hours)	O2a	9/05/2013	10/05 - 6/06	6/06/2013	67.0	70.5	81.0	52.5	59.0	76.5
CM1		O2b	10/05/2013	11/05 - 7/06	7/06/2013	92.0	87.5	67.0	79.0	77.0	88.0

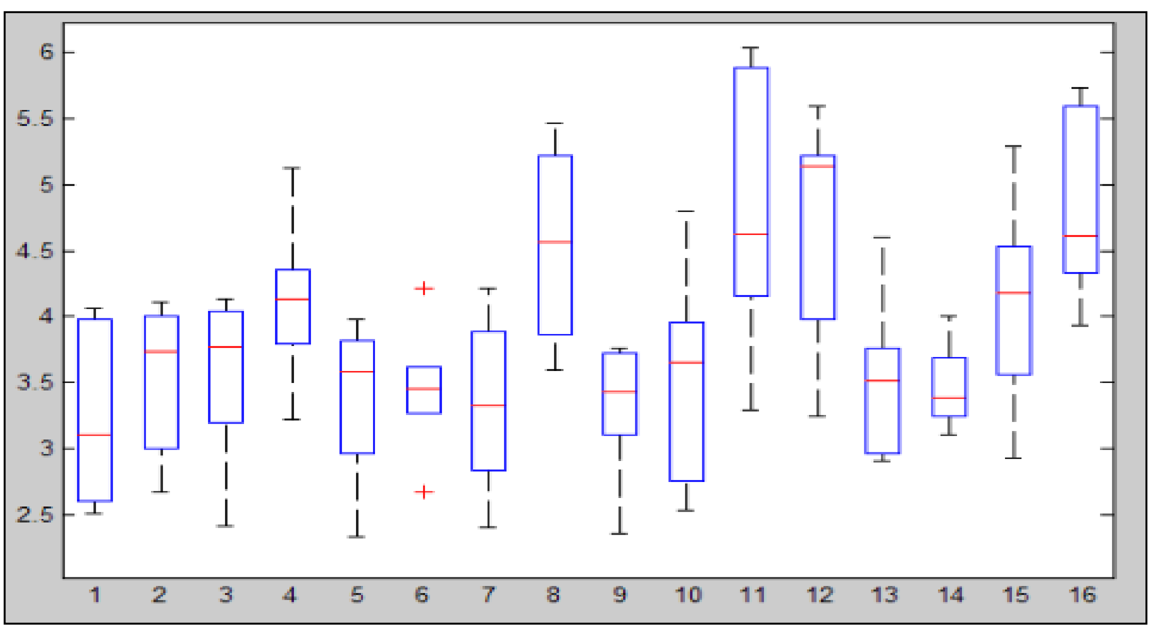
Appendix B – Box plots

The box plots for the bond strength data was performed on MATLAB with the left hand axis representing the bond strength and the bottom axis representing the test number according to the results sheet illustrated in appendix A. A total of 8 outliers were recorded across all of the tested composite specimens, with Substrate 1 containing three outliers, and substrate 2 and 3 including two and four outliers respectively.

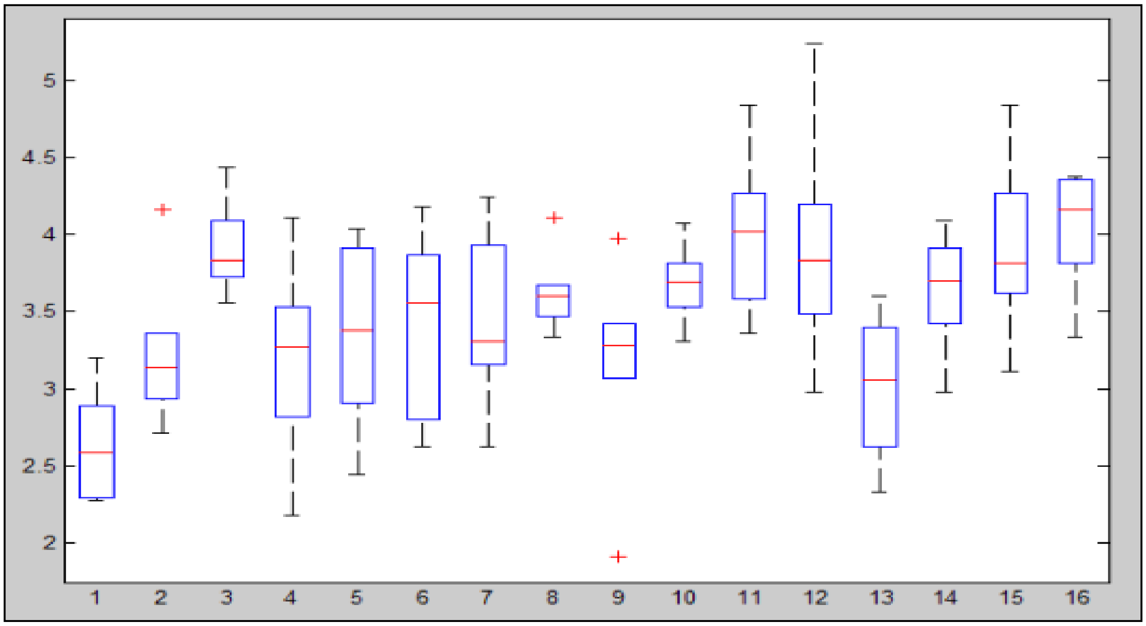
Substrate 1



Substrate 2



Substrate 3



MATLAB produces a box plot of the data in (x). Therefore each row of data represented in appendix A was converted to a column matrix (x). This allowed the program to create one box plot per column matrix. On each box (for all substrates) the red line represents the median of the data, whereas the edges of the box are the 25th and 75th percentiles. The whiskers, which are illustrated by the dotted lines, represent the most extreme data points while not including the outliers. Outliers are marked individually with red crosses.

Once the outliers were established within the data, they were analysed and removed before any statistical analysis was performed. Outliers have the potential to distort results and inflate errors.

Appendix C – Raw material properties

Klipheuwel sand

SIEVE ANALYSIS

Uct Concrete Laboratory

Aggregate sample: Klipheuwel sand

1000g

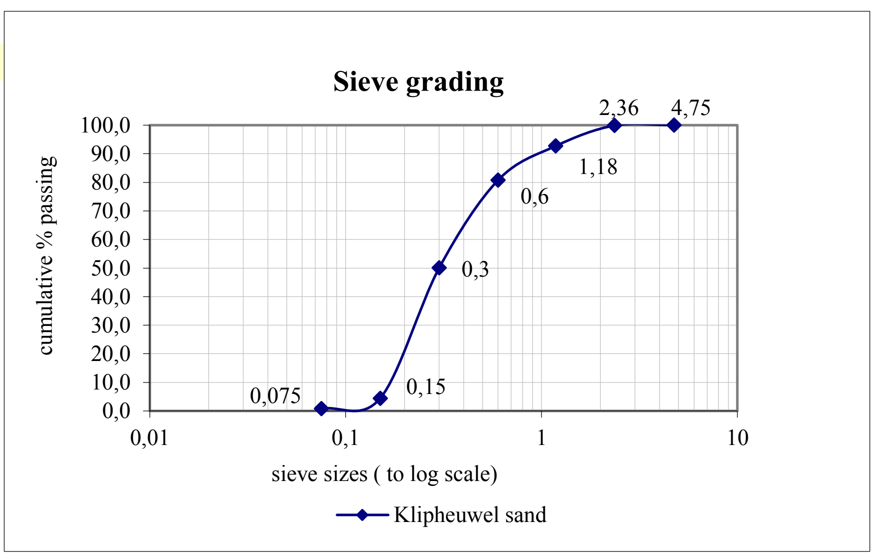
Test No: 3

Date: 06/2012

Tested by: Cmay/Elvino

Finess Modulus: 1.7

Sieve opening (mm)	MASS Sieve (g)	MASS Sieve + aggr. (g)	MASS retained (g)	Mass retained %	cum. Retained (%)	cum. % passing (%)
4.75	437.6	437.6	0.0	0.0	0.0	100.0
2.36	413.0	414.2	1.2	0.1	0.1	99.9
1.18	548.3	620.1	71.8	7.2	7.3	92.7
0.6	502.7	621.9	119.2	11.9	19.2	80.8
0.3	490.4	797.4	307.0	30.7	50.0	50.0
0.15	473.4	929.1	455.7	45.6	95.6	4.4
0.075	261.3	297.2	35.9	3.6	99.2	0.8
PAN	457.2	465.5	8.3	0.8		
		sum mass	999.1			



Dune sand (new batch)

SIEVE ANALYSIS

Uct Concrete Laboratory

Aggregate sample:

New dune sand

1000g

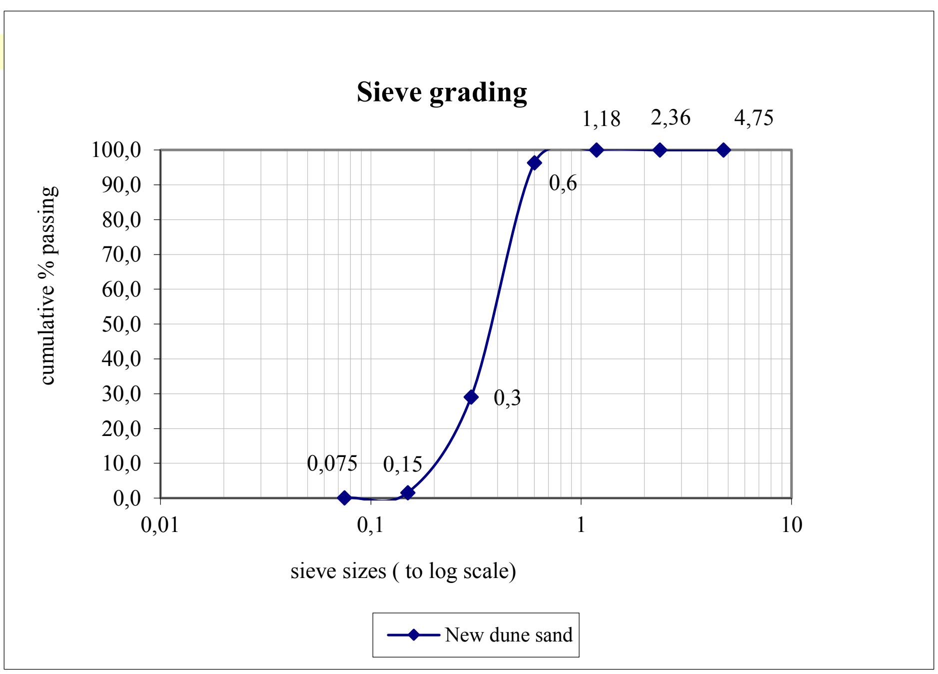
Test No: 1

Date: 06/12/2012

Tested by: Elvino

Finess Modulus: 1.7

Sieve opening (mm)	MASS Sieve (g)	MASS Sieve + aggr. (g)	MASS retained (g)	Mass retained %	cum. Retained (%)	cum. % passing (%)
4.75	437.0	437.0	0.0	0.0	0.0	100.0
2.36	420.0	420.0	0.0	0.0	0.0	100.0
1.18	552.0	552.0	0.0	0.0	0.0	100.0
0.6	514.0	551.0	37.0	3.7	3.7	96.3
0.3	477.0	1149.0	672.0	67.2	70.9	29.1
0.15	489.0	764.0	275.0	27.5	98.4	1.6
0.075	254.0	269.0	15.0	1.5	99.9	0.1
PAN	475.0	476.0	1.0	0.1		
		sum mass	1000.0			



Dune sand (old batch)

SIEVE ANALYSIS

Uct Concrete Laboratory

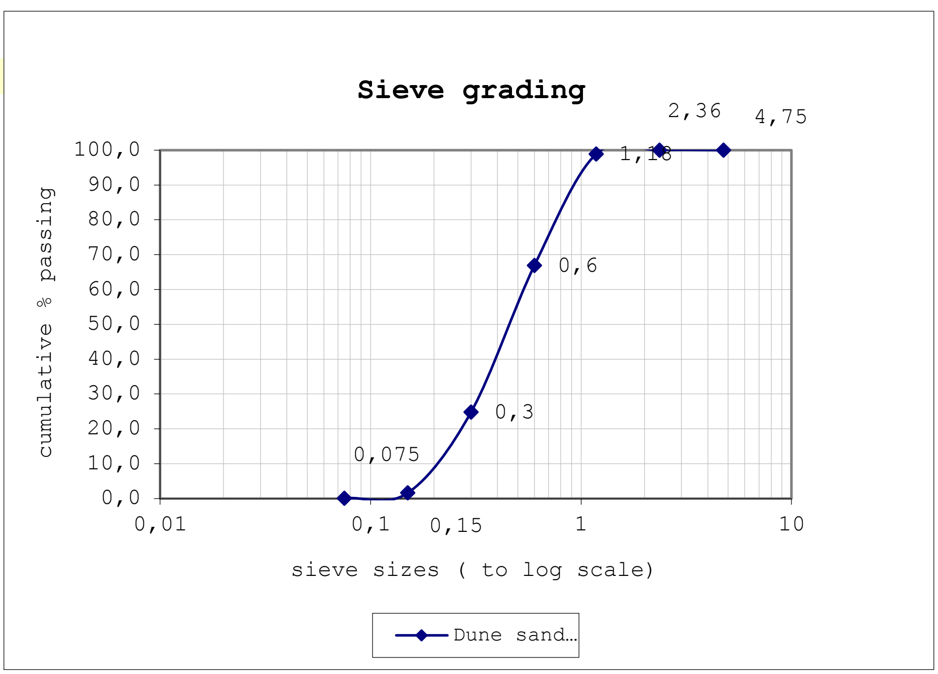
Aggregate sample: **Dune sand (old batch)**

1000g

Test No: 1
Date: 16/10/2012
Tested by: Elvino

Finess Modulus: 2.1

Sieve opening (mm)	MASS Sieve (g)	MASS Sieve + aggr. (g)	MASS retained (g)	Mass retained %	cum. Retained (%)	cum. % passing (%)
4.75	437.0	437.0	0.0	0.0	0.0	100.0
2.36	420.0	420.0	0.0	0.0	0.0	100.0
1.18	552.0	563.0	11.0	1.1	1.1	98.9
0.6	514.0	834.0	320.0	32.0	33.1	66.9
0.3	477.0	898.0	421.0	42.1	75.2	24.8
0.15	470.0	702.0	232.0	23.2	98.4	1.6
0.075	433.0	448.0	15.0	1.5	99.9	0.1
PAN	242.0	243.0	1.0	0.1		
		sum mass	1000.0			



Appendix D – Permeability and water sorptivity

The durability index tests which were performed to characterise the three different concrete substrates, namely: Oxygen permeability and water sorptivity tests, were carried out according to the 'durability testing manual (version 2.0)' by Alexander *et al,* (2010).

Sample preparation

The same samples were used for both the OPI and water sorptivity tests and were created with the identically mix designs as the three tested substrates. Three 100mm concrete cubes were cast for each substrate and after 28days of water curing at a temperature of 27-30°C, the concrete specimens were cored. Once coring was completed, the specimens were cut into 30 ± 2mm discs and marked samples 1, 2, 3, 4 according to their respective substrates. The discs were then placed into a drying oven at a temperature of 50 ± 2°C for 7 days. Once the drying of the samples was completed, the two DI tests were carried out with the first being the OPI.

Oxygen Permeability test (OPI)

The OPI test is a laboratory test method which measures the air permeation through a concrete surface. This test method is suitable for the evaluation of resources and concrete mixes for design purposes and can also be used for quality control of concrete on site. The classification of the OPI values of the substrate concrete was of importance, as the concrete structure may influence how the overlay concrete interacts with the substrate. Below the testing procedure is described.

Preconditioning of test specimens

Once the samples have been oven dried for 7 days in order to rid the any moisture, the test specimens are then placed into a desiccator for no less than 2 hours and no more than 4 hours. This process ensures that the specimens cool to an appropriate room temperature without any ingress of moisture from the atmosphere. The dimensions of each specimen are then measured using a vernier calliper with an accuracy of ± 0.02mm (Alexander *et al,* 2010). The specimens are now ready for the OPI test.

Oxygen permeability index test procedure

The specimens are firstly removed from the desiccators for thirty minutes and then placed in a rubber sealed steel collar. The steel collar is then placed on top of the test chamber or pressure cell as to ensure that there are no leaks which occur during testing. Thereafter the inlet and outlet pipes of the oxygen permeability cell are opened to purge any gases other than the oxygen supplied by the cell. The typical OPI apparatus set up is illustrated in figure D1.

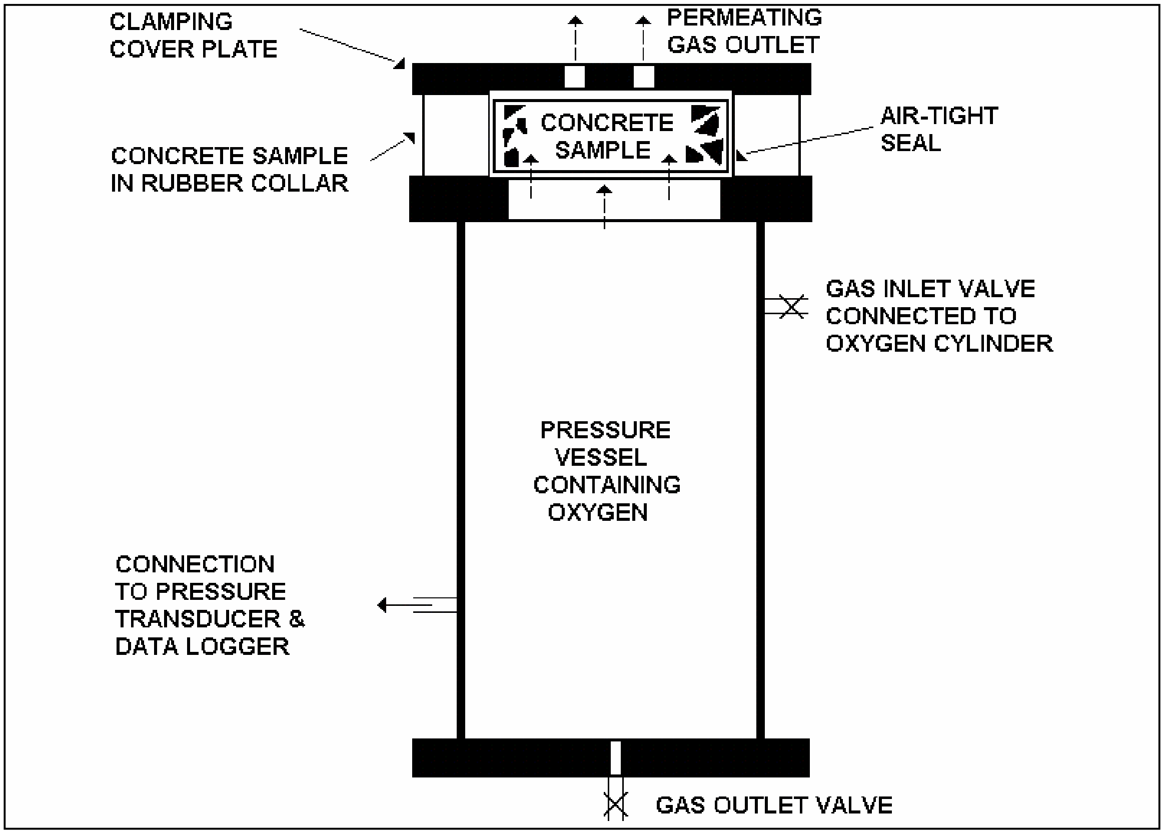


Figure D1: Permeability cell arrangement (UCT DI testing manual)

The pressure cell is pressurised to 100 ± 5 kPa and then automatically monitored for pressure decay (oxygen passing through the specimen). The experimental test may be terminated after 6 hours ± 5min, or when the pressure of the cell drops below 50 ± 2 kPa.

Water sorptivity test

The water sorptivity test was established to measure how quickly liquids travel through concrete through the concretes absorption properties. This test measure is suitable for the evaluation of resources and concrete mixes for design purposes, and can also be used for quality control of concrete on site. The water sorptivity test which was used to characterise the substrates was necessary to investigate whether substrate properties influenced bond strength or not.

Preconditioning of test specimens

The test specimens which were utilised for the water sorptivity tests were the same specimens from which were tested in the OPI test. Therefore, no preconditioning was required for the test samples, provided that no moisture has penetrated the specimens and that the test be conducted straight after the OPI test. If the test can't be performed, place the specimens in the 50 ± 2°C oven over night and then in the desiccator as before prior to experimental testing.

Water sorptivity test procedure

Since the specimens were already precondition and measured, the next step was to tape the bottom of each specimen with masking tape. Once each specimen has been taped, 10 layers of paper towel were placed on a tray as illustrated in figure D2. Calcium hydroxide solution was then poured into the tray ensuring that there were no bubbles present within the paper. Once the paper was fully saturated with the solution the specimens were weighed (dry mass) to an accuracy of 0.01g at time 0. The specimens were then placed immediately on the paper towel and weighed at intervals of 3, 5, 7, 9, 12, 15, 20 and 25 minutes.

Figure D2: Water sorptivity specimens on paper towel

Once the weighing of the specimens was completed, they were placed in a vacuum saturation tank for a maximum of 1 day with the tape still attached. The tank was firstly maintained between -75 and -80 kPa for 3 hours. After the 3 hours, calcium hydroxide saturate was incorporated into the tank at 40mm above the specimens. The vacuum was re-established between -75 and –80 kPa for a further hour. Once this time elapsed the vacuum was removed and the specimens were allowed to soak for a further 18 hours. The specimens were then weighed and was recorded as the saturated mass. The calculations for the water sorptivity test can be found in 'durability testing manual (version 2.0)' by Alexander *et al*, (2010).

Appendix E – Ethics Form

EBE Faculty: Assessment of Ethics in Research Projects

Any person planning to undertake research in the Faculty of Engineering and the Built Environment at the University of Cape Town is required to complete this form before collecting or analysing data. When completed it should be submitted to the supervisor (where applicable) and from there to the Head of Department.

If any of the questions below have been answered YES, and the applicant is NOT a fourth year student, the Head should forward this form for approval by the Faculty EIR committee: submit to Ms Zulpha Geyer - Zulpha.Geyer@uct.ac.za; Chemical Engineering Building, Upper Campus, UCT, (Ph 021 650 4791).

NB: A copy of this completed form must be included with the thesis/dissertation/report when it is submitted for examination.

Name of Principal Researcher/Student: Marco Talotti Department: Civil engineering

Preferred email address of applicant: marco_talotti@hotmail.com

If a Student: yes Degree: MSc Civil Engineering Supervisor: A/Prof Hans Beushausen

If a Research Contract indicate source of funding/sponsorship:

Research Project Title: Influence of substrate moisture preparation on bonded concrete overlays

Overview of ethics issues in your research project:

Question 1: Is there a possibility that your research could cause harm to a third party (i.e. a person not involved in your project)?	~~YES~~	NO
Question 2: Is your research making use of human subjects as sources of data? If your answer is YES, please complete Addendum 2.	~~YES~~	NO
Question 3: Does your research involve the participation of or provision of services to communities? If your answer is YES, please complete Addendum 3.	~~YES~~	NO
Question 4: If your research is sponsored, is there any potential for conflicts of interest? If your answer is YES, please complete Addendum 4.	~~YES~~	NO

If you have answered YES to any of the above questions, please append a copy of your research proposal, as well as any interview schedules or questionnaires (Addendum 1) and please complete further addenda as appropriate.

I hereby undertake to carry out my research in such a way that

- there is no apparent legal objection to the nature or the method of research; and
- the research will not compromise staff or students or the other responsibilities of the University;
- the stated objective will be achieved, and the findings will have a high degree of validity;
- limitations and alternative interpretations will be considered;
- the findings could be subject to peer review and publicly available; and
- I will comply with the conventions of copyright and avoid any practice that would constitute plagiarism.

Signed by:	Full name and signature	Date
Principal Researcher/Student:		

This application is approved by:

Supervisor (if applicable):		
HOD (or delegated nominee): Final authority for all assessments with NO to all questions and for all undergraduate research.		
Chair : Faculty EIR Committee For applicants other than undergraduate students who have answered YES to any of the above questions.		

ADDENDUM1:

Please append a copy of the research proposal here, as well as any interview schedules or questionnaires

ADDENDUM 2: To be completed if you answered YES to Question 2:

It is assumed that you have read the UCT Code for Research involving Human Subjects (available at http://web.uct.ac.za/depts/educate/download/uctcodeforresearchinvolvinghumansubjects.pdf) in order to be able to answer the questions in this addendum.

2.1 Does the research discriminate against participation by individuals, or differentiate between participants, on the grounds of gender, race or ethnic group, age range, religion, income, handicap, illness or any similar classification?	YES	NO
2.2 Does the research require the participation of socially or physically vulnerable people (children, aged, disabled, etc) or legally restricted groups?	YES	NO
2.3 Will you not be able to secure the informed consent of all participants in the research? (In the case of children, will you not be able to obtain the consent of their guardians or parents?)	YES	NO
2.4 Will any confidential data be collected or will identifiable records of individuals be kept?	YES	NO
2.5 In reporting on this research is there any possibility that you will not be able to keep the identities of the individuals involved anonymous?	YES	NO
2.6 Are there any foreseeable risks of physical, psychological or social harm to participants that might occur in the course of the research?	YES	NO
2.7 Does the research include making payments or giving gifts to any participants?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 3: To be completed if you answered YES to Question 3:

3.1 Is the community expected to make decisions for, during or based on the research?	YES	NO
3.2 At the end of the research will any economic or social process be terminated or left unsupported, or equipment or facilities used in the research be recovered from the participants or community?	YES	NO
3.3 Will any service be provided at a level below the generally accepted standards?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues:

ADDENDUM 4: To be completed if you answered YES to Question 4

4.1 Is there any existing or potential conflict of interest between a research sponsor, academic supervisor, other researchers or participants?	YES	NO
4.2 Will information that reveals the identity of participants be supplied to a research sponsor, other than with the permission of the individuals?	YES	NO
4.3 Does the proposed research potentially conflict with the research of any other individual or group within the University?	YES	NO

If you have answered YES to any of these questions, please describe below how you plan to address these issues: